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TRADEOFFS IN THE MODULARIZATION OF LARGE FUSION SYSTEMS

by

Marilyn Kelley McQuade

B.S., Massachusetts Institute of Technology

(1977)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS OF THE

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at the

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December 1981

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TRADEOFFS IN THE MODULARIZATION OF LARGE FUSION SYSTEMS

by

Marilyn Kelley McQuade

Submitted to the Department of Nuclear Engineering on December 1981, in partial fulfillment of the requirements for the Degree of Master of Science in Nuclear Engineering.

ABSTRACT

The modularization of magnetic confinement fusion systems was investigated, with an immediate view to facilitating maintenance and repair, and an ultimate view of maximizing commercial fusion reactor availability. The advantages and disadvantages of modularization versus unitary construction were examined for the reactor plant in the construction phase, and for vacuum walls, dewars, support structures and magnet coils in the operational phase. A brief examination of remote handling was included, since remotely operated equipment will be vital to the design and success of any modularization configuration.

Particular emphasis was placed on magnet systems since they are, to a large degree, the heart of any magnetic fusion reactor; they are large, complex and technologically demanding; and their modularization and reliability are especially controversial.

Thesis Supervisor: Dr. Lawrence M. Lidsky
Title: Professor of Nuclear Engineering

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CHAPTER 1. INTRODUCTION

1.1 Satisfying Utility Requirements

The goal of fusion research and development is the successful incorporation of fusion power plants into the commercial electrical generation system. For this to happen, such plants must meet public electric utility criteria for safety, reliability and economy. A brief survey of these criteria will provide a measure against which modular system designs can be gauged.

Obviously, full-blown safety, health and environmental regulations for fusion power plants do not yet exist (although large-scale experimental projects must conform to existing laws), but when they are formulated, they are unlikely to be less stringent regarding permissible consequences of emissions or accidents than those pertaining to fission plants. The first wall and blanket of D-T reactors will accumulate copious fluences of 14-Mev neutrons, with the result that they will become quite radioactive. The problems surrounding their handling and disposition will in large measure be similar to fission waste problems.

Modularity of fusion reactors, in whatever form, will probably not influence the basic outer containment structure, and thus its impact on emissions to the environment will be minimal. But its effects on accidents and internal emissions, due to leaks, missiles and various malfunctions remain to be considered. For example, seals and seams be-

tween modules will have to be tight to tritium.

Reliability requirements for individual power generation stations depend on the overall reliability goals of the utility, and are governed by:

1. Demand for electricity (load), which in turn is a function of time of day, day of week and weather conditions;

2. Numbers, types and sizes of electrical generating units available to the utility; and

3. Costs.

B.K. Jensen, et al, mentioned that "... reliability refers to adequacy of the generation system to meet the projected load."[1] The traditional industry practice has been to design to such a level of reliability that the system will only be unable to meet the load a total of one day in ten years, an unreliability of about 3×10^{-4}.[2] Since utilities maintain excess capacity in the form of reserve that is typically 20% - 25% above expected peak load, and normally have an arrangement for buying, selling and sharing electricity with other utilities, the reliability of individual generating facilities need not be as great as that of the utility as a whole.

Fusion reactors will be baseline generating units, that is, large, capital intensive and comparatively ef-

ficient plants meant to operate at full power 24 hours a day. Base load units typically have capacity factors of 65% - 85%, capacity factor being defined as "... the ratio of the total energy generated in a given period (usually a month or a year) to the total energy generation which would occur if the plant were operated at full power during the same period."[3] Assuming full power operation, then, the allowed downtime is 15% - 35% of a year, or 8-18 weeks. Most fusion reactor designs call for a capacity factor of 70% - 80%, leaving an allowed downtime of 10-15 weeks per year. Of this downtime, 4-6 weeks must be earmarked for scheduled maintenance, permitting a forced outage rate of 6-11 weeks per year.

Capacity factor is to be distinguished from availability, which is the percentage of time that a device is available for use, whether it is used or not. For example, small "peaking" units, operated by utilities to meet peak loads, might be available for use, say, 80% of the time, but are only used about 25% of the time. The availability of such a unit is 80%. The distinction is not so crucial in discussing baseload commercial units, which are supposed to run at rated power all the time, but it is quite important in talking about experimental and demonstration reactors.

Utilities always seek to minimize costs, consistent with

the safety and reliability requirements mentioned earlier. Costs are broadly classified as either capital costs or operations and maintenance costs. Baseload generation plants, and especially nuclear reactors, have quite high capital costs compared with intermediate and peaking units, but are usually more efficient and less expensive (per kilowatt-hour generated) to operate. For fusion to be competitive, it will obviously have to produce electricity at costs comparable to those of other generating options. Determining in advance, however, the costs associated with any new type of technology is very difficult, and if experience with fission power plants is any indicator, initial cost appraisals are likely to be underestimates.

Nuclear Engineering International has observed that "Fusion reactors could cost more than four times as much to build as light water fission reactors," and that for a tokamak, "...it is estimated that more than 50kt of steel would be required for a 1500 MW fusion reactor. The cost of the steel alone is more than the cost of any complete, present-day power station."[4]

The cost impacts of modularity will be felt both in the plant construction phase, where there are definite practical limits to the size of modules that can be transported; and especially in the operational phase, where almost the entire idea of "going modular" is to facilitate or even make possible certain maintenance procedures.

1.2 What is Meant by Modularity?

Before addressing the pros and cons associated with modularity, it is necessary to know what is meant by the term module, or modular. The literature uses the word loosely, with the assumption that the meaning is obvious to all, but in fact, the term itself tends to conjure up merely the idea of "cut up into or made out of pieces." But how many pieces? How big? Need they be nearly identical, or interchangeable? Does the same idea of modularity apply for a plant under construction as for an operational one?

Some ore specific questions will help to make the problem of definition clearer. If a tokamak is designed so as to be taken apart only by halves, is it modularly constructed? Most people would say *no*, but that it would be if it could come apart in twelve sections. The notion here is that a twelfth part of a torus, being nearly cylindrical, presents a tractable geometry for dealing with such matters as replacement of a first wall section, whereas half a torus does not.

Is an automobile modular? The intuitive answer, again, is *no*. An automobile does indeed comprise a large number of dissimilar parts, but many of them are replaceable only with considerable difficulty. For a car to be "modular" in the intuitive sense, it would probably be composed of, say, three to five sections which have the following

features:

1. They would be easily detached and reattached to one another;
2. Any one of them could be replaced if one of its constituent parts caused trouble; and
3. Each one would be cheap enough that, in the event of a breakdown, one module would be replaced rather than the car being traded in.

Third, is a brick wall modular? The answer depends largely on whether it is under construction or already built. From the point of view of the builder, the wall is modular, because the pieces for it can be readily transported to the construction site and assembled there without the need for on-site large-scale manufacturing facilities. Once the wall is built, however, it remains permanently in one piece, and anyone wishing to replace one brick will definitely not consider it modular.

Without trying to give an all-inclusive and completely precise definition of modularity, then, it will at least have the following features:

1. Modules fit together in a simple geometric fashion, at least conceptually. (There may be complicated fastenings, etc., in real life, which would not in themselves nullify modularity).

2. If associated with construction, modules are pieces of the finished product small enough to be transported but complete enough to reduce the amount of site dedicated to assembly or to preclude the need for extensive on-site manufacturing facilities.

3. If associated with operations and maintenance, a modularly constructed device is easier to put together, take apart and handle than one which is constructed "in one piece".

4. A module can be taken out and replaced with a duplicate, though it is not necessary that all the modules required to constitute a complete device be identical.

5. Replacement cost of a module does not represent the lion's share of what it would cost to replace the entire device.

6. Modularity implies that the constituent parts of a module that is separated from the corporate entity, are more or less easily accessible.

Some moduarization will be necessary for any magnetically confined fusion device, since whatever the geometry, the first wall and blanket will require periodic replacement. When designers deem necessary the modularization of such structures as magnet windings, helium dewars and vacuum vessels, it is usually because of the need for access to the first wall or blanket, or for repairs or maintenance on the machine.

CHAPTER 2. CONSTRUCTION PHASE

2.1 Siting

As mentioned earlier, modularity during the construction phase of a plant need not correspond with what is modular in the finished one. Indeed, given the enormous sizes and weights of many single modules in conceptual designs, it would be impossible for the two to correspond exactly.

It is very likely that the plant site for a fusion reactor will be similar to that of a fission plant, or for that matter, almost any large electrical power facility. The following features will be required:

1. It must be near an adequate supply of coolant for waste heat;
2. it must be far enough from any large population center to minimize health risks, both from routine plant emissions, and from accidents;
3. it should be in an area where the risks from natural disasters, e.g., earthquakes or tornadoes, are low;
4. it should be conveniently accessible to the largest type of transportation that will be required for plant construction and maintenance;

5. it should be reasonably close to housing, schools, health services, etc., for plant personnel and their families, and to telephone, water and sewage lines;
6. it should be large enough (the minimum size for a fission plant is about 450 acres[5]);
7. it should be reasonable in cost;
8. it should be acceptable to the local populace.

The location of the site will obviously have a direct bearing on the type of transportation to be used for the construction, and thus on the maximum sizes and weights that can be transported.

2.2 Transportation

Materials for, and portions of, a facility can be transported by land, water or air, and each method has advantages and disadvantages. Transportation over land via transporter, a vehicle which is essentially a flatbed on caterpillar treads (see Figure 1), is in order when the distance involved is short--normally under thirty miles. Perhaps the most dramatic example of this type of movement is that of NASA's space shuttle, when taken from its hangar to the launch site. Its 2250 tons was moved, at a speed of one mile per hour, by a single transporter. More typical

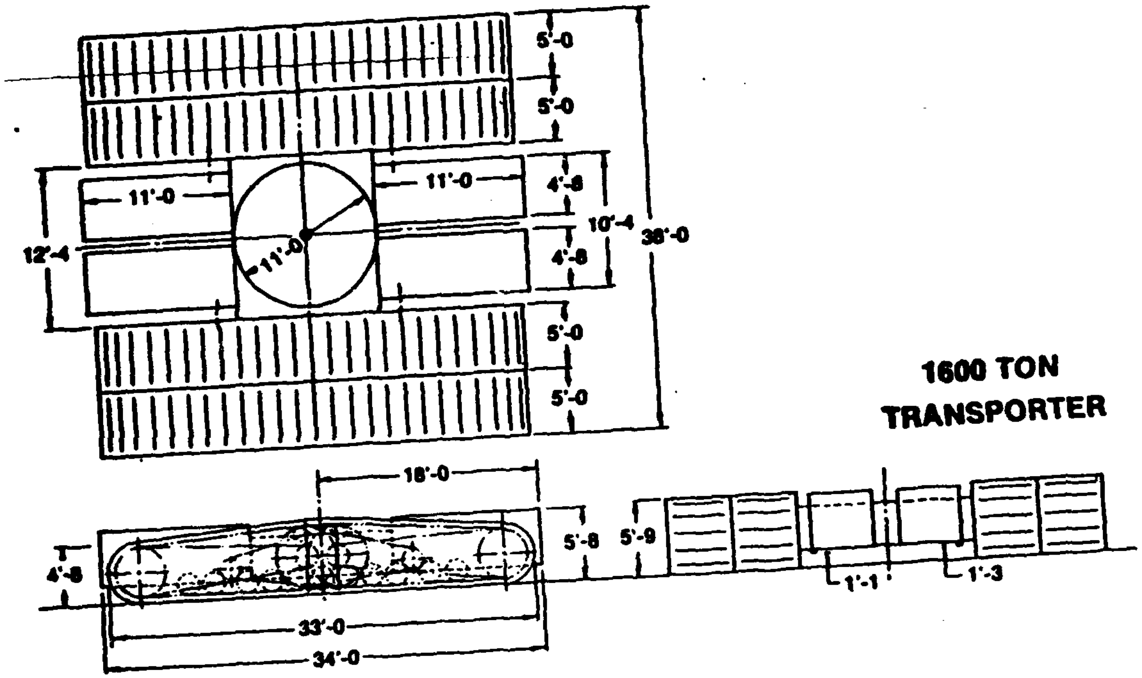

1600 TON
TRANSPORTER
5'-0
5'-0
4'-8
4'-8
10'-4
38'-0
5'-0
5'-0
11'-0
11'-0
11'-0
12'-4
18'-0
5'-8
5'-9
4'-8
33'-0
34'-0
1'-1
1'-3

Figure 1.[6]

transporter capacities range from 400 to 1600 tons, and the latter figure should be taken as a safe upper limit. The vehicles are operable over unimproved surfaces as well as highways, a feature which makes them suitable for transition-type handling, such as transferring an object from a ship to a nearby onshore location. For example, the Belding Corporation used transporters to move a 1000 ton fission reactor from a barge to a storage site half a mile away. The move, which included a dry run with concrete blocks simulating the reactor weight, took four hours and cost nearly $100,000.[7]

The use of transporters is usually limited not only to short distances but to low speeds, typically on the order of three miles per hour or less (the cost of one move in which a team of transporters hauled a 2237 ton load a distance of 200 miles was over $5,000,000!)[8]. Operations involving these vehicles are quite expensive, and only pay when their capacity, maneuverability and off-road capability are required.

Part of the enormous cost incurred in using transporters and dolly systems to transport heavy overland loads is, of course, the use of the equipment and the labor involved. Another part comprises the permits and clearance surveys demanded by state transportation departments when oversize and overweight loads are moved on public roads. The Belding report lists several of the permit charges, which vary

considerably from state to state:

- one state charges $5 per permit per item;
- another charges $1 per ton per mile;
- Iowa charges a flat fee of $1,000 per load;
- A certain 27-mile stretch of highway in Illinois can involve several hundred dollars in permits for oversize loads.[9]

The clearance survey, which literally determines whether the load will fit under bridges and overpasses along the desired route, can cost several thousand dollars. The survey also spells out what changes must be made in the topology of the various routes considered, such as building temporary roads, cutting down trees or moving pipelines. All this makes it quite evident that transporting loads of the magnitude described over the highways is no trivial matter.

Movement of heavy equipment by rail is considerably cheaper, when it can be done. Typical heavy hauling rail cars have capacities of up to 500 tons, and speeds of around 25 miles per hour. Especially large rail cars, called Schnabel cars, to be used particularly for transporting large nuclear equipment, will have capacities up to 800 tons. Greater tonnages can be accommodated if the load is so configured as to be compatible with tandem hauling. Even

so, very few rail bridges are rated to bear such loads, and this places strict limitations on the weight that can be moved over a given rail route.

An even more restrictive constraint that weight, however, is size. Many of the tunnels in the United States railway system, particularly in the Northeast, can accommodate loads only fourteen feet in diameter, about 4.3 meters. Clearly, something like a UWMAK-III toroidal field coil, which measures about 15 meters wide by 24 meters high, could never negotiate such a tunnel in one piece. In some cases, special handling, involving perhaps laying temporary track or piecing together a route using the facilities of several railroads, can stretch the maximum dimensions of a load, but the limitations remain quite severe. The widest payload carried so far overland by rail has been just under ten meters.[10]

Air transportation has the obvious advantage of speed. Restrictions on payload and size, however, rule it out for many applications. The 747 cargo aircraft is limited to loads of about 122 tons and ten feet high. The C5-A, a military transport plane, has a capacity of 100 tons, but can accommodate loads having a girth of up to 57 feet.[11] Air Force regulations, however, forbid any use of military transports which would give the appearance of competition with commercial carriers, so by the time fusion reactors become commercially available, the use of the C5-A to transport

plant components will probably be unavailable. The cost of using either plane varies with distance, time and load, but a single one-way trip can be expected to cost between $25,000 and $60,000.

Such is the present state of air cargo handling. Some industry representatives believe that a 160-ton capacity airship is possible with today's technology, the only obstacle being the question of who will pick up the tab for development and building. Also, the future may see the development of lighter-than-air systems with capacities of up to 500 tons, at greatly reduced speed, of course. Eventual production of such aircraft is by no means certain, though, and should not be counted on as a solution to the problems of handling fusion reactor components in transit.

For really big and heavy loads, the answer is water transportation. Barges can handle loads of a size and weight that would be nearly impossible to move by any other means. Barges with capacities well in excess of 3,000 tons are common, and a 3,000 ton load can be carried in any water that is at least twelve feet deep. Smaller loads, of cours, require even less depth. Moreoever, the coastlines, rivers and Great Lakes, which form the navigable waterways of the United States, comprise about 12,000 miles of usable passage.[12]

Still, water is not the absolutely ideal solution. To make effective use of this form of transportation, both

manufacturer and plant should be located very close to serviceable water, ideally, close enough so that what land movement is required will avoid the use of public roads. Furthermore, the western U.S., roughly marked off by a line running from the eastern border of North Dakota to Houston, Texas, is largely devoid of navigable rivers, leaving only the coast for possible plant sites, should barge service be required. Finally, when it becomes necessary to ship from the east to the west by water, the Panama Canal must be used, adding considerably to the time and expense involved. A price tag of over $500,000 is not unheard of for such an operation. By contrast, for shipments between points in the east, the cost is on the order of $50,000 to $100,000.

In conclusion, it is desirable, if not necessary, from the point of view of construction and transportation, to keep the size and weight of any shipment small enough, in order to minimize expenses and transit time. If possible, then, a very large fusion plant component, even if it is designed never to be taken apart once in operation, should be made and shipped in smaller pieces, to be permanently joined together on site.

2.3 Construction Cranes

Construction and maintenance of the reactor facility will require the use of cranes as a matter of course.

The cranes must be suited to the jobs in terms of size, capacity, reliability and cost, and must furthermore be capable of precision and remote handling. Many of the hoisting and moving tasks, of course, are not peculiar to fusion power and its attendant facilities. A great deal of the construction, for example, will involve the lifting of big, heavy loads (several hundred tons), and moving them around without damage and with a reasonable degree of precision. This is nothing new to the crane industry, which is quite capable of supplying construction cranes with capacities of up to 1250 tons or more. A certain gantry crane in Malmo, Sweden, has a span of 600 feet and a capacity of 1650 tons.[13] Load capacity, in fact, is one of the least limiting constraints to be dealt with; almost any weight object that could conceivably be needed for a fusion power plant could be lifted and moved with existing cranes.

Economy, however, may dictate that consideration be given to the difference between loads that will be lifted during construction and those that will be dealt with during maintenance or replacement in the course of the plant lifetime. If the difference is large, say a factor of two or more, it may be more cost-effective to lease the larger capacity crane for construction only, and just pay for as much permanent capacity as will be needed after plant startup. If the difference is small, the permanent crane may double as a construction crane.

Obviously, many factors besides weight are important in considering fusion plant cranes, and much of industry's experience with fission reactor plants is probably applicable, particularly in the matter of hoisting radioactive loads. The Nuclear Regulatory Commission's NUREG-0554, "Single-Failure Proof Cranes for Nuclear Power Plants", goes into some detail about crane and hoisting system requirements, several of which are summarized here:

- A crane handling system that moves a critical load (one which, if improperly handled, could result in a release of radioactivity) should be single-failure proof. That is, it should be designed with sufficient redundancy that a failure of one load-bearing component will not result in the load being dropped or damaged.

- The design rated load should be 15% greater than the maximum anticipated critical load.

- "The operating environment, including maximum and minimum pressure, maximum rate of pressure increase, temperature, humidity, and emergency corrosive or hazardous conditions, should be specified for the crane and lifting fixtures."[1]

- Material properties should meet certain ASTM or ASME specifications, or pass specified alternative tests.

• Cranes should be designed to withstand earthquakes and to maintain control of a load during a seismic event; in other words, they should be seismically designed.

• In the event of a breakdown in the automatic controls or the electrical system, or immobilization due to component malfunction, appropriate means (e.g., manual control) should be available for safe handling of the load.

• Conservative design and/or redundancy is specified for nearly all crane system components, including reeving system, braking systems, ropes, lifting devices (such as hooks, slings, etc.), bridge, trolley and driver. Satisfying these requirements presents little or no problem to manufacturers, since fission reactor facilities have been around for years.

Remote and precision handling are important characteristics for handling of radioactive loads, even though, in the course of normal operation, cranes for neither fission nor fusion plants encounter significant radiation, and radiation damage to hoisting devices is negligible. Nevertheless, the occasional necessity to move large radioactive loads makes remote handling imperative. This can be done in two ways:

• The controls for crane operation can be remote, involving long lengths of electrical cable between operator and crane. Tangling, wear and fatigue on these cables then

become a concern, although judicious design can minimize the problem.

• The controls can be located on the crane itself, and be operated by means of radio signals. This eliminates the need for long wires, but required maintenance on the receiver and controls makes this option less "remote" than the other. This would pose a problem only in the event that the crane-mounted controls failed during the lifting of a critical load.

Precision handling of large loads imposes two additional constraints: first, the load obviously must be positioned precisely, and second, significant swaying in load handling is normally to be avoided, for instance, in cramped quarters where swaying could result in collision with other large objects.

Precision placement cannot be done purely automatically; that is, the operator cannot "set it and forget it". Present crane systems have rather wide tolerances (e.g., between trolley wheels and track, although some of this can be eliminated by using, say, notched wheels on a V-shaped track), and repeated identical settings on the controls can result in final load locations several inches apart. The use of cameras and human-operated controls for final positioning can, however, place a load exactly where it is wanted.

Swaying can be limited by the use of anti-sway reeving, in which the ropes used to lift the load lead to widely

separated points on the trolley. This technique has an important drawback in the present state of the art; it has not yet been used with redundancy.

Fusion plants will be very large, some typical designs calling for reactor rooms around 300 feet in diameter. The facility's polar crane must span this length. A crane with the required span and capacity is possible, but must be made in several pieces, since the maximum length for shipping purposes is about 135 feet. The 300 foot crane bridge, therefore, would have to be made in three pieces and assembled on site. Since the crane is one of the major pieces of plant equipment, the facility must be designed with it in mind. For example, to minimize the time and effort needed to position the crane lifting device, the plant layout should ideally be circular, a feature that is happily inherent in toroidal reactors. Moreover, delicate and heavy objects that will be lifted regularly should have included in their design features that make for safe and easy handling by lifting equipment.

Compared with other fusion plant costs, the price of the polar crane will be small. A 100 foot span, 500 ton capacity crane today sells for about $2,000,000. The polar crane for a fusion plant, being longer and of greater capacity, will probably cost several times that. Seismic design adds another 20% or so to the cost, and single-failure proof design another several hundred thousand

dollars. With the entire plant likely to cost several billion dollars, the crane is a relatively small investment.

CHAPTER 3. MAINTENANCE AND REPAIR

The ultimate goal of the fusion program is to build reactors that can be used to produce electricity safely, cheaply and reliably, and any action taken in regard to these devices should further this goal. The immediate goal of maintenance and repair, then, is to interrupt operation of the plant as little as possible, and to avert future interruptions as much as possible. Modularity has long been recognized as an important part of attaining this goal.

Maintenance and repair have overlapping functions, but for present purposes will be distinguished. Maintenance is routinely scheduled work intended to keep the plant in good working order, and to forestall costly, time-consuming and unscheduled breakdowns. Repair is work done in response to an unscheduled or unforeseen malfunction. The two may in part involve exactly the same operations. For example, routine maintenance will include the periodic replacement of portions of the first wall, before they have degraded to the extent that they impair the operation or integrity of the rest of the reactor. If part of the first wall fails prematurely, however, its replacement is termed repair, and the repair operation is likely to extend to other reactors components and be considerably more involved. Nonetheless, the two operations have much in common. The reactor must be shut down in both cases, and much the same procedure will be needed to gain access to the

relevant components.

The optimum allocation between maintenance and repair will be that which results in shortest overall downtime and least repair and replacement costs. By definition, maintenance can be scheduled, while repair cannot, and so time for the latter must be allocated on the basis of carefully predetermined probabilities. Scheduling maintenance so as to make the probability of any malfunction, say, 10^{-6}/year, would leave very little time for operating the plant even if it were possible. Instead, it must be scheduled to leave the probabilities of breakdowns of the various components something that can be lived with, while permitting a decent availability for the plant.

This discussion will focus on the concerns facing fusion system designers in the areas of access, handling, reliability and remote maintenance, and will concentrate on the peculiar problems associated with three types of magnetic confinement schemes: tokamaks, stellarators and tandem mirrors. Furthermore, primary attention will be devoted to the problems of magnet systems, since these systems, because of their importance, size, complexity and delicacy, represent some of the toughest difficulties in the way of modularization.

3.1 Access

Downtime of any reactor will be significantly influenced by the time it takes to repair or replace relevant

portions of the machine, and this in turn depends on their accessibility. Of the three types of design to be considered, the tokamak has received the most attention. Tokamaks are almost always modularized radially, as shown in Figure 2, to allow access at least to components inside the vacuum wall.

A simple schematic cross section of a toamak arrangement is depicted in Figure 3, with three locations to be considered for access. Location "A" might be the site of a dewar leak, for example, or a local "hot spot" in a TF coil. The small reactor aspect ratio and the presence of the support column make in situ access to "A" impossible, even with remote maintenance equipment. The module in which it is located must be retracted from the main body of the reactor in order for repair to take place. Location "B" is the first wall, also inaccessible in situ, but in addition requiring dismantling of the module once the module has been retracted. Location "C", a PF coil inside the TF coils but outside the vacuum wall, might not demand the retraction of the entire module for access. If, for example, both the dewar and the TF coil were demountable in such a way as to allow the top halves to be removed, and if the OH coils retracted, the PF coil could be accessed in situ. The advantages of this approach include:

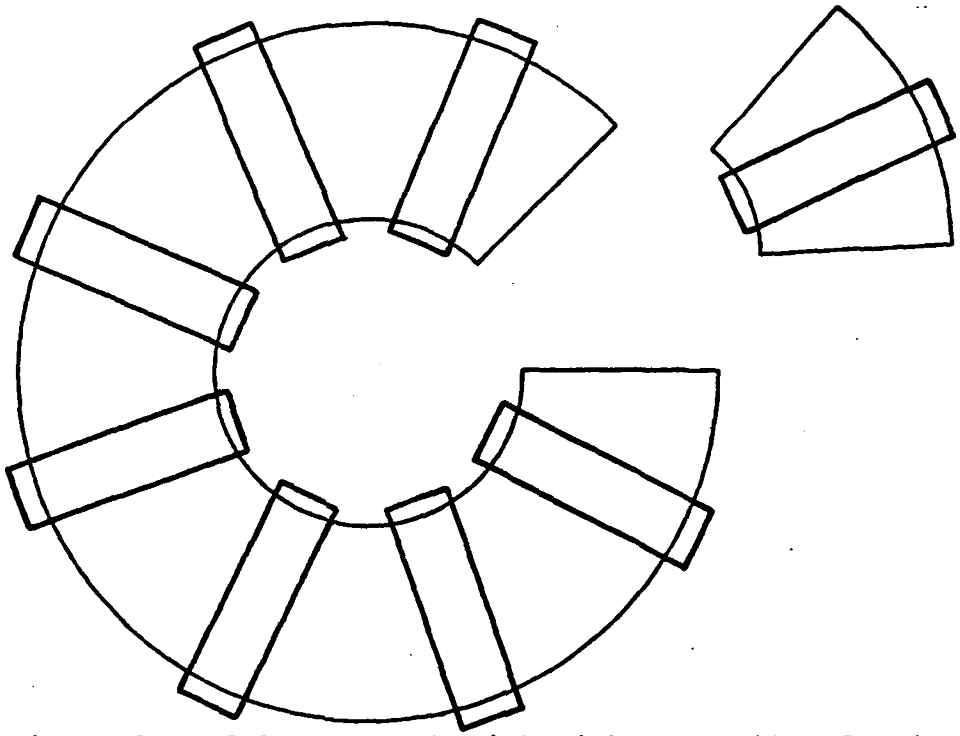


Figure 2. Modular Tokamak with Eight TF Coils, Showing One Module Retracted.

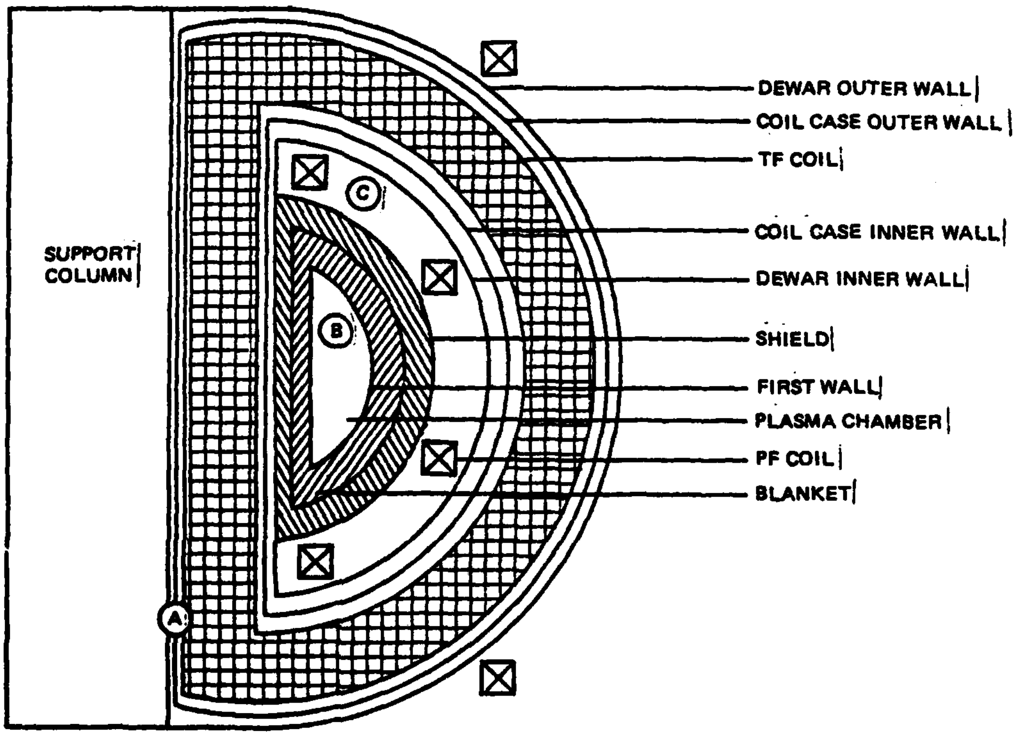


Figure 3. Schematic Cross Section of a Tokamak, Omitting Most Structural Support.

1. It is likely to be quicker and cheaper than moving an entire module;
2. the plasma chamber, which is intensely radioactive, is not exposed, thus permitting contact maintenance or repair;
3. the vacuum seal remains intact, at least in this configuration. This is no small advantage, since the extremely high vacua, on the order of 10^{-8} torr, required for reactor operation, are difficult to achieve, especially for the large volume encompassed by the vacuum wall.

3.2 Vacuum Walls

The INTOR Group of the IAEA Workshop described the state of the art of vacuum pumping of helium as inadequate,[15] and Coffman, et al, of the U.S. Department of Energy, branded it primitive.[16] Clearly, significant advances in vacuum technique are necessary, since the vacuum system is crucial to the reactor operation. A pressure of 10^{-8} torr is on the threshold of ultra high vacuum, which, to produce at all, requires highly specialized, though well known, techniques. The size of the evacuated space will present a problem, since it will be on the order of

$$V = 2\pi^2 Ra^2,$$

where V = evacuated volume

R = major radius

a = minor radius. (1)

For typical tokamak dimensions, with an R of 6.5 m and an a of 1.7 m, the volume will be about 370 m^3, and this is only the volume enclosed by the first wall. By contrast, a vessel considered large for purposes of ultra high vacuum attainment might be 0.4 m^3.[17] Achieving a thousand-fold increase in evacuated volume is ambitious, and assuming that it can be done, it will be time-consuming and costly. Richard Moore, of Princeton Plasma Physics Laboratory (PPPL), reports on an experiment in which a 340ℓ/s pump took over 28 hours to evacuate a 0.1 m^3 chamber from 10^{-5} torr to 10^{-8} torr.[18] Pumping speeds for a typical tokamak will be required to be 10^6 - 10^7 ℓ/s and more, over two orders of magnitude faster that present individual pumps. Part of the problem is alleviated by having a dozen or so vacuum pumps, but progress in this area is certainly necessary. In any event, opening the ultra-high vacuum chamber is a task to be undertaken as seldom as possible.

The configuration shown in Figure 3 is by no means the only arrangement possible for a tokamak. Where to put the vacuum wall(s) is one of the major decisions facing the

fusion systems designers. G.M. Fuller, et al, of McDonnell Douglas Astronautics Company, have identified three general locations for vacuum walls, and a reactor may have more than one, each maintaining a different vacuum level. The different locations are summarized in Table 1, and depicted in Figure 4.

The literature is inconsistent in the use of the terms primary, secondary, etc., when referring to vacuum containment. "Primary" can mean either the innermost or the outermost vacuum wall, the latter usage being the one used by McDonnell Douglas, and which will be adopted here.

In nearly all designs, the secondary, or even tertiary, vacuum wall is within the TF coils. Vacuum pumping considerations given above make it desirable that this wall, which encloses the ultra high vacuum, be as close as practicable to the first wall, in order to minimize volume (one scenario for the ORNL Cassette tokamak has the secondary vacuum chamber being the plasma chamber itself). But there are advantages to having the vacuum wall located further out. If it is outside of the blanket, it is more accessible, and it is conceivable that some repairs to it could be made in situ, and this is desirable if the wall is less reliable than the components it encloses.

Can the innermost vacuum wall be made modular, and if so, what would be the best way to do it? By definition, a modular vacuum wall is one that is easy to take apart

TABLE 1

TOKAMAK VACUUM WALL LOCATIONS

Location/ Possible Vacuum (Torr)	750	10^{-4}	10^{-6}	10^{-8}
Reactor Room Wall	X	X		
TF coil/ Outer Shield		X	X	
Blanket/ LSAP				X

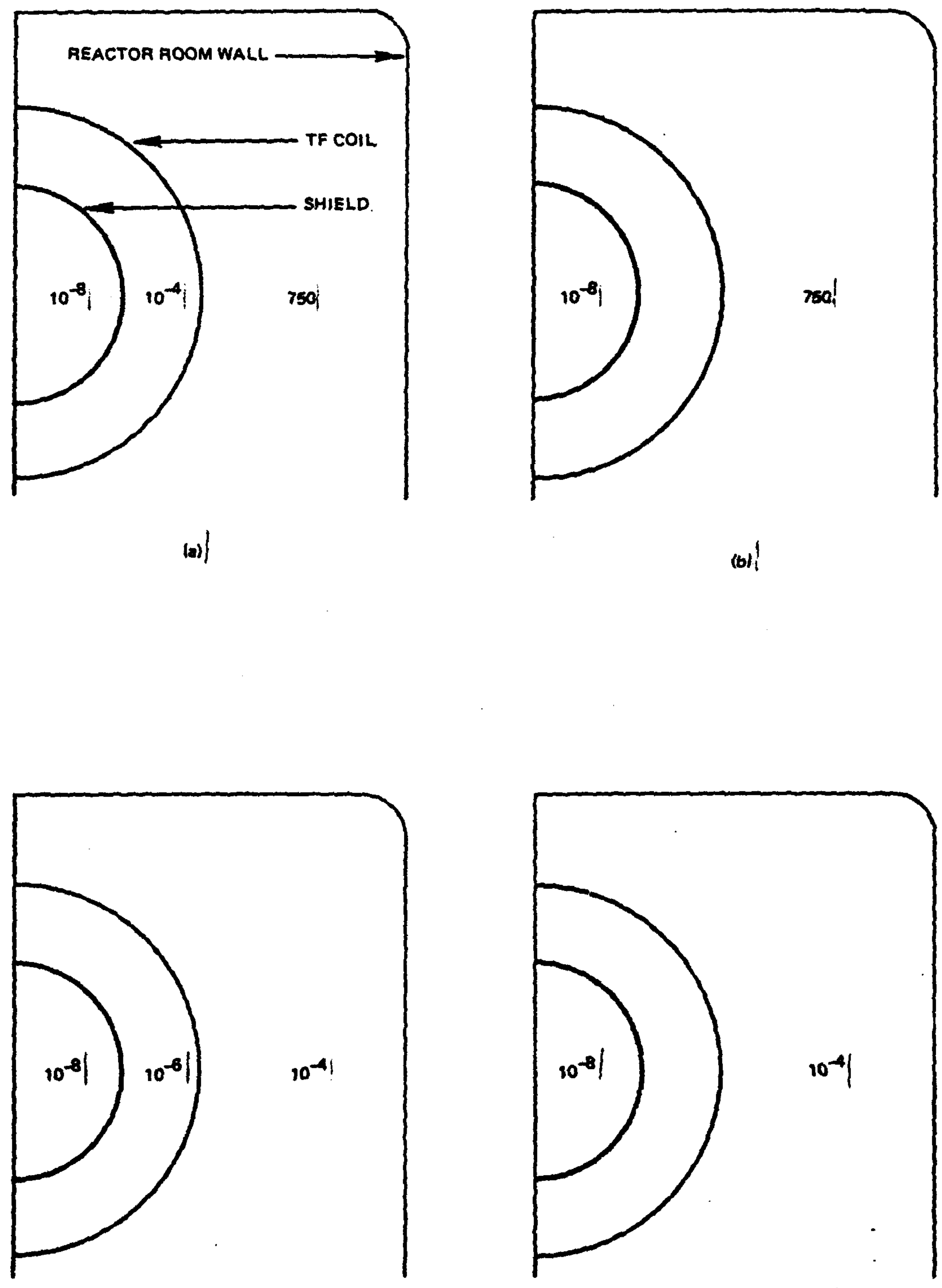


Figure 4. Possible Vacuum Wall Arrangements.[19]

and this means that the sections must be joined by an operable fastening. A welded wall is not modular. But operable seals are leakier than permanent ones, and so the question becomes, "What is the allowable pressure difference across the fastening which would produce a leak rate capable of being handled feasibly by the pumping system?"

Part of the motivation for having a primary vacuum at, say, 10^{-4} torr, surrounding the secondary one, is to permit the secondary vacuum to have demountable seals. It is easier, of course, and permits greater latitude in the choice of joining options, to maintain a vacuum when the outside pressure is 10,000 times greater than when it is 100,000,000,000 times greater. But the latter can be done. Roth lists no fewer than 18 demountable all-metal ultra high vacuum seals alone (Table 2) and mentions a number of criteria:

> Very often the various vacuum seals should conform to special requirements. Among these requirements the most important ones are: resistance to high temperatures and/or low temperatures including temperature cycling, and resistance to chemical corrosion (or radiation damage)...
>
> Demountable seals used in bakeable ultra-high vacuum systems should conform to the severe requirements summarized as follows:

TABLE 2[20]

ALL METAL ULTRA-HIGH VACUUM VALVES

Valve designation: Closing	Sealing System	Operating	Valve Port	Conductance (l./sec): Open	Conductance (l./sec): Closed	Leak Rate (lusec)	Remarks
Kovar nose on copper	Kovar diaphragm	Differential Screw	6 mm dia.	0.3	10^{-11}-10^{-12}	--	See Fig. 6.93
Speedivac MCV 1			0.1 in.^{2}	--	10^{-10}-10^{-11}	--	Bakeable up to 450°C
Alpert type valve			--	0.5	--	$<10^{-7}$	Bakeable up to 450°C; Plate 34a
Silver gasket between Monel nose and seat	Nickel Diaphragm	Screw	--	1	10^{-14}	--	See Fig. 6.101a
Monel nose on steel	--	--	--	1	10^{-14}	--	See Fig. 6.94 Heated at 450°C
Alpert type valve		--	--	3	$<10^{-10}$	--	See Fig. 6.95 Heated at 200°C
Copper gasket on metal seat	Gasket seals	Lever arm	25mm	13	10^{-11}	--	See Fig. 6.104 Heated at 150°C
Aluminium Gasket	--	--	--	13	--	10^{-10}	See Fig. 6.101b

(cont'd)

TABLE 2 (cont'd)

Valve Designation: Closing	Sealing System	Operating	Valve Port	Open Conductance (l./sec)	Closed Conductance (l./sec)	Leak Rate (lusec)	Remarks
Gold or Silver Plate	bellows	--	--	35	3×10^{-14}	$< 2 \times 10^{-8}$	--
Monel cone on stainless steel	--	Screw and cam	--	20	--	$< 10^{-7}$	Bakeable up to 450°C
Copper gasket on stainless steel seat	--	--	1 1/2 in.	38	--	--	see Fig. 6.102 Bakeable 300°C
Speedivac MCV 4	--	--	1 in.^{2}	--	10^{-8}-10^{-9}	--	Bakeable 450°C
Copper gasket on metal seat	--	--	50 mm	55	--	10^{-8}	Up to 150°C
Copper nose on stainless steel	bellows	mechanical	2 in.	100	10^{-9}	--	Fig. 6.99
Copper nose on stainless steel	bellows	mechanical	2 in.	100	10^{-10}	--	Bakeable 400°C

(cont'd)

TABLE 2 (cont'd)

Valve Designation: Closing	Sealing System	Operating	Valve Port	Conductance (l./sec): Open	Closed	Leak Rate (lusec)	Remarks
Metal cone on Monel seal	--	hydraulic	--	140	--	10^{-6}	Bakeable 450°C Fast Acting (1 sec)
Stain-less Steel Spherical Nose on Silver Seat	bellows	--	4 in.	200	10^{-12}	--	--
Copper Poppet on Copper Seat	bellows	hydraulic	8-3/4 in.	2100	$7x10^{-7}$	10^{-9}	Fig. 6.96

1. Leak rates lower than 10^{-6} lusec in the whole temperature range from room temperature at 500°C...

2. The leak rate must not be influenced by repeated heating and subsequent cooling.

3. The seal should not contain materials having, even at 500°C, vapour pressures high than the ultimate pressusre to be reached (e.g., 10^{-9} torr).

4. The joints should be simple to assemble and to dismantle.

5. The seal should be able to be reused many times with the same gasket, or at least without the need to remake the finish of the flange faces.

6. The seal sould be easily machined, and obviously at the lowest cost.[21]

Another motivation for the primary vacuum, and one less easily overcome, is to keep the required strength, and thus the required size, of the secondary wall down to manageable proportions. The space inside the TF coils is cramped enough without adding large volumes of dead weight whose only justification is brute strength. A wall need not be very strong to withstand an overpressure of 10^{-4} torr.

The primary vacuum wall, if any, is usually located outside of any field magnets, and for present purposes will be taken to support a vacuum of 10^{-4} torr. Since it is, by definition, the outermost vacuum wall (with the possible exception of a slight underpressure encompassing the entire plant), it must withstand an inwardly directed net presure of about an atmosphere. Typical placements for this

wall are the shield/lateral support access panel (LSAP) or the reactor room itself.

Some of the problems associated with the shield/LSAP location are similar to those of the secondary wall. Access to the blanket on first wall can only be gained by breaking the vacuum and opening the wall. It must, therefore, be modular, the joined with demountable fastenings. Furthermore, the volume enclosed is much larger, increasing the likelihood of leaks forming, and requiring high structural strength. This massive wall must in turn be supported, since it cannot be fixed to the floor of the plant because of the need for trucks and other equipment to retract the reactor modules. However, maintaining a 10^{-4} torr vacuum is far more tractable than maintaining one of 10^{-8} torr, and neither the seals nor the materials need be as elaborate as those for the secondary wall.

The notion of a complete building being evacuated seems at first glance to be even more formidable. Farfaletti-Casali and Reiter estimate the volume of the reactor building at 2.5×10^5 m^3,[22] and the difference in volume between the entire building and the shield/LSAP enclosure is not to be taken lightly. Nevertheless, placing the primary vacuum containment at this location has definite advantages. It can be made in one piece, rather than modular, since access within it is limited more by the presence of the vacuum than by the wall configura-

tion. For example, maintenance and monitoring equipment can be placed within it permanently. Even contact maintenance, where otherwise not contraindicated, need not be ruled out; pressure suits may make it more cumbersome, but are certainly possible, and may well be a more attractive maintenance and repair option than remote operation.

Most of the considerations mentioned above for tokamaks apply to stellarators as well. Van Schiver, et al[23], at the University of Wisconsin, have considered one design in which the secondary wall is inside the helical windings and one in which it is outside them. Placed inside the windings, the wall reduces the space available to the plasma chamber, first wall and blanket, but permits access to the windings without breaking the vacuum, an operation which would be necessary if the wall were placed outside the windings.

Stellarators typically have larger aspect ratios than do tokamaks, and do not require a central support column. Consequently, location "A" of Figure 3 on a stellarator may be sufficiently accessible in situ to preclude the necessity of retracting a reactor module, a feature which represents a distinct maintainability advantage of the stellarator over the tokamak. The geometry of the tandem mirror, of course, is even more tractable. The complicated configuration of the end plugs, though, makes it difficult or im-

possible to situate the secondary vacuum wall inside the magnets, and, therefore, it must surround them.

3.3 Support Structures

The vacuum wall or walls are not the only obstacles to free access to the heart of a fusion reactor. Large amounts of structural support are needed for the following reasons:

1. To bear the sheer weight of the reactor, typically tens of thousands of tons;
2. to contain radioactive material, and in the event of an accident, any missiles;
3. to maintain the reactor configuration in the face of large, and often unbalanced magnetic forces. This problem is severest for tokamaks and some forms of modular stellarators.

Each module of a reactor will require a separate support beneath it in the form of a large-capacity truck or dolly, so that the segments can be individually retracted from the reactor. Capacities exist for most of the range of estimated module weights, from a few hundred tons to about 5,000 tons, but in the case of the largest weights or of odd shapes (such as wedges for toroidal devices), the truck will most likely have to be custom-made. This type of support, however, is an aid, rather than a hindrance, to reactor access. The structures needed for internal

support, to keep the reactor configured properly, and to counteract magnet stresses are the ones that will get in the way. Bond and Last list seven types of stresses on the Joint European Tokamak poloidal fields coils alone:

> The inner poloidal coils are subject to:
>
> a. forces due to the poloidal magnetic field, which cause tensile hoop stresses and axial compressive stresses;
>
> b. axial compression due to magnetic forces acting on the iron transformer core, which have to be transmitted through the coils;
>
> c. the external radial inward pressure due to the toroidal coils, which cause compressive hoop stresses ...
>
> d. temperature rises due to the currents flowing in them, which cause various stresses;
>
> e. surface shear forces due to relative axial movement between the toroidal and poloidal coils, due to different rates and times of thermal and mechanical expansion;
>
> f. surface shear forces due to tangential movement of the toroidal coils and fluted column, when twisted by poloidal fields;
>
> g. internal pressure due to interference fit on steel support rings.[24]

This list does not even include stresses on the PF coils which occur when a single TF coil discharges, leaving all other TF coils operating normally. Figures 5-8 depict the stresses on PF coils due both to a normally operating TF coil system and due to such a system when one TF coil is discharged. These figures show that, even under nominal conditions, these forces, though balanced overall, are

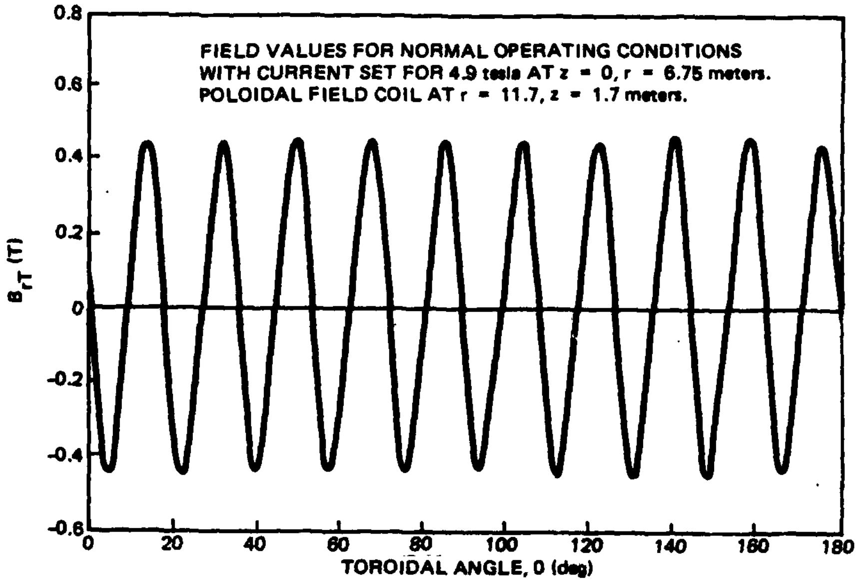


Figure 5.[25]

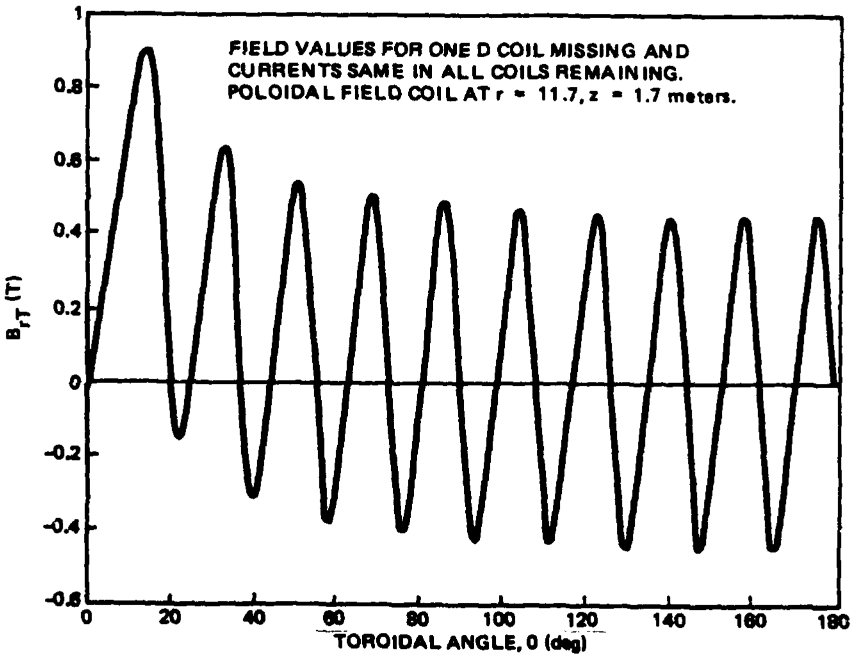


Figure 6.[26]

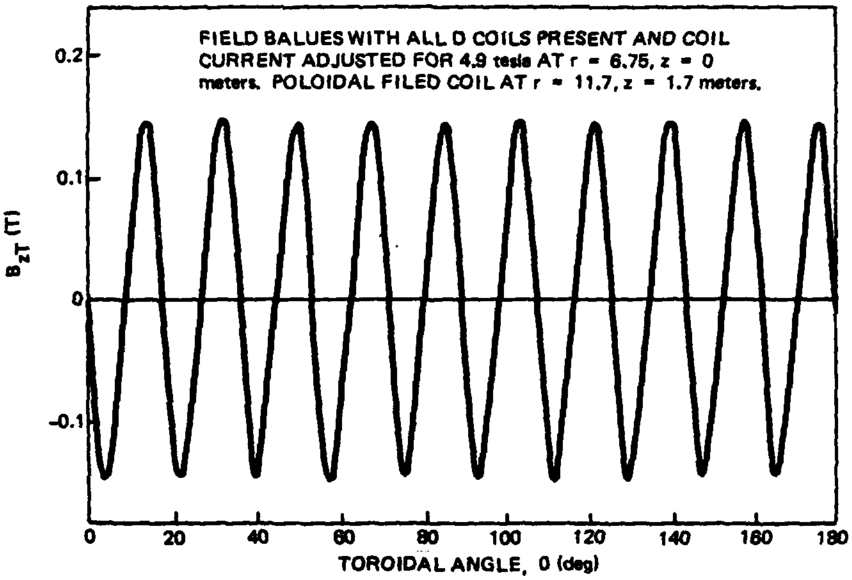


Figure 7.[27]

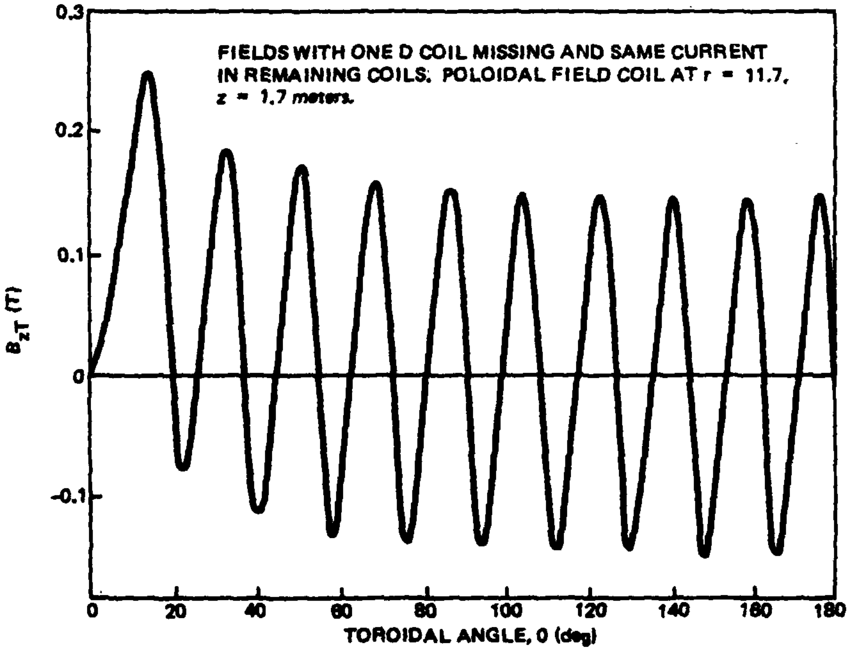


Figure 8.[28]

not spacially uniform, but are periodic. Moreover, because the fields are pulsed, the forces are temporally nonuniform as well, placing an even higher demand on supporting structures.

Tokamak TF coils will store tens to hundreds of gigajoules of magnetic energy, and will, like the PF coils, be pulsed. Because of the internal stresses, structural support is needed not only between magnets, but around them, and the latter commonly takes the form in conceptual designs of a stainless steel or titanium case, three to six cm thick, which surrounds each TF coil. Since the function of the coil case is structural support only, and it does not have to be tight to fluids, it can be made demountable by using bolts instead of welds at appropriate places should access to the coil itself become necessary. As a minimum, the case should be split in half longitudinally, so that the coil can be completely removed. It would also be desirable to have one or more pairs of lateral joints, especially when the coil is demountable, since not all maintenance or repair situations would then warrant undoing the case entirely (Figure 9).

Supports between and outside of the coil cases should likewise be made demountable, so that when magnetic forces are absent, which will occur almost any time repairs or maintenance are necessary, they can be easily disassembled. Once disassembled, though, can the structural supports be

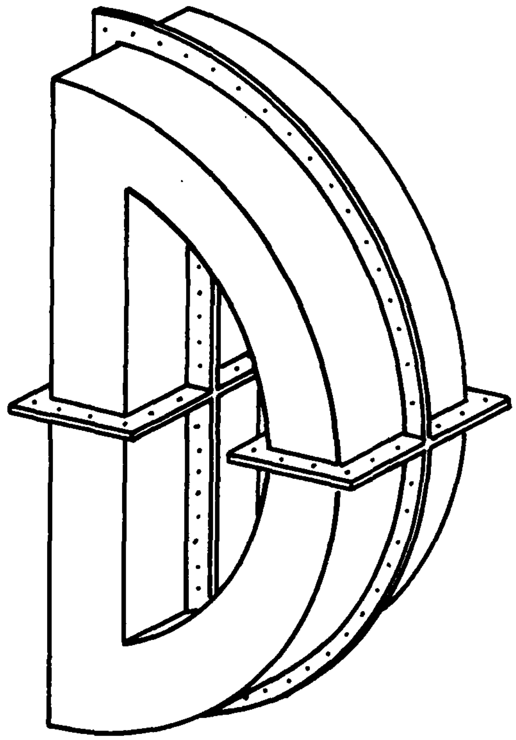


Figure 9. Demountable TF Coil Case

easily reassembled? The stresses that they will have to sustain entail that the supports be made very large, massive and complicated. For reasonable ease of reassembly, then, they must be more than strong; they must have a high modulus of elasticity, to prevent load inequalities between them from putting them far out of alignment. The prospect of re-aligning perhaps several dozen holes on a structure which supports several hundred tons can be imagined by anyone who has ever had to change an automobile tire, but magnified many times over. An alternative to at least some bolts might be a sleevelike clamp which would fit over the flanges where support structure modules meet (Figure 10), an arrangement in which precise alignment is not so crucial.

All three types of reactors under consideration here will require support for their large superconducting magnets, even if at times only for the purpose of sustaining static loads. The weight of the Mirror Fusion Test Facility (MFTF) magnets

is about 314 tons a piece[29] and that of a power reactor magnet can be expected to be over 900 tons. The magnetic force loads for tokamaks have been mentioned, with the observation that the toroidal geometry complicates the problem. Yet the magnet forces even in the simpler geometry of the tandem mirror can be significant. Indeed, as R.H. Bulmer of Lawrence Livermore Laboratory remarks, "MFTF-B support loads are dominated by the magnetic component (not gravity and seismic loads)."[30] A list of the forces experienced by the MFTF-B magnets is given in Table 3, and a schematic of the barrier coil support module is shown in Figure 11.

The virial theorem places a lower theoretical limit on the mass of structure required to support magnetic forces, and is stated:

$$M_T - M_C = \frac{\rho E}{\sigma}, \tag{3}$$

where M_T is the mass of the structure in tension, M_C is the mass of structure in compression, ρ is the density of

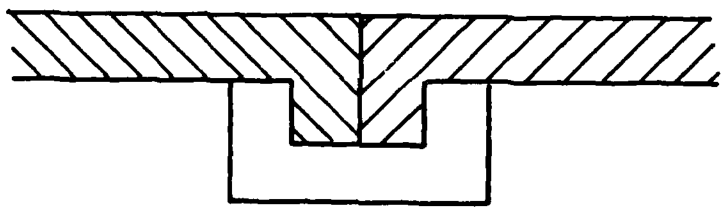


Figure 10. Cross Section of Support Structure Module Flanges Joined by a Clamp.

TABLE 3[31]

AXIAL MAGNETIC LOADS FOR NORMAL OPERATING CURRENTS

Coil Identification		Force, 10^3 lb	
		Simple tandem	Tandem with Barrier
Solenoid	S1	14	-7
Solenoid	S2	32	-32
Solenoid	S3	34	-164
Solenoid	S4	33	-710
Solenoid	S5	40	8
Barrier	B1	0	-64
Barrier	B2	0	-640
Solenoid	S6	85	-790
Solenoid	S7	327	0
Transition	T1	1036	1204
Plug	M1	1152	1300
Plug	M2	-3110	-3068

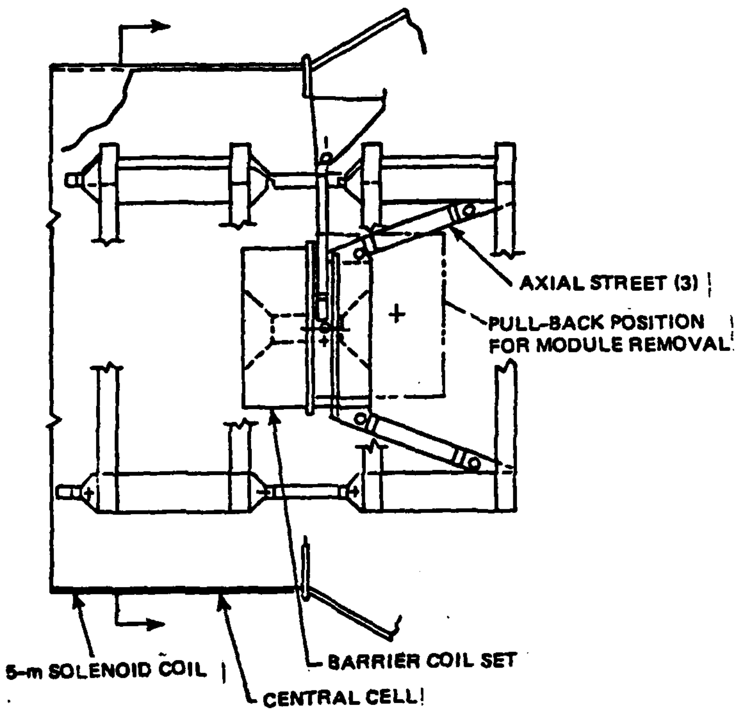


Figure 11. An Efficient Barrier Coil Support System.[32]

the structure material, E is the magnetic energy and σ is the allowable stress. For example, stainless steel has a density of about 0.28 lbm/in^3, and an allowable stress in many reactor designs of 6×10^4 psi. If the magnet system stores 200 GJ of magnetic energy, the virial theorem amount, that is, $\rho E/\sigma$, amounts to over 3,700 tons. A real reactor will require about three times the virial theorem amount, in this case, over 11,000 tons, of support material.

Generalization about magnetic forces in stellarators is not as straightfoward as with other reactor types. Stellarator windings can take many shapes, the variables including discrete versus continuous coils; the poloidal field period number ℓ, the toroidal field period number m; number of coils, if discrete; distortions in the θ - Z plane, that is, making discrete coils three-dimensional; and distortions in the minor radial direction, that is, making discrete coils non-circular. Tradeoffs involved in choice of coil configuration, including the so-called modular stellarator, will be discussed later, but it should be noted here that magnetic forces, and thus, magnet structural supports, depend strongly on coil configuration. Hence, while physics considerations are likely to dominate the overall reactor magnet design, (especially in experimental and demonstration reactors), it must be borne in mind that support requirements will impact available space and reactor

access, and must not be neglected. T.K. Chu, et al, observe that for classical stellarator, with toroidally continuous windings, "The support structure of the windings is usually massive because of the $\bar{J} \times \bar{B}$ forces on the coil. This structure occupies a large magnetic volume which might otherwise be used for plasma confinement or other purposes."[33] On the other hand, for the "modular" stellarator, where the term modular means "having discrete coils", "...there is no inwardly directed force. Thus, the support structure can be located outside and on the sides of the coils."[34] This is an obvious advantage from a maintenance and repair standpoint, since any support structure necessarily impedes reactor access, and even with a large aspect ratio device, such as a stellarator, the "hole of the doughnut" will probably be pretty cramped. The less space there taken up by supports, the better.

3.4 Magnet Dewars

Nearly all conceptual fusion reactors proposed for demonstration or commercial application incorporate some superconducting magnet coils in their designs, and these coils are usually very large. Besides requiring coil cases for support, therefore, these magnets will need continuous cooling, and this means enclosing them in a dewar, or cryostat. Several dewar options are possible when the superconducting coils are discrete. A dewar can be common

to all coils, shared by just a few, or individual. In addition to the primary dewar, containing usually liquid helium, there may be an outer dewar containing liquid nitrogen. Finally, a given crystat can have one or two layers of superinsulation. In each case, there are tradeoffs among complexity, costs, accessibility and reliability.

Many tokamak designs, though not all, are such that only the TF coils are superconducting, and the PF, OH and other coils are *normal*. A dewar common to all the TF coils could naively be thought of as two nested hollow tubes bent into a torus and between which fit the TF coils. The naive picture must, of course, be heavily modified to correspond with reality. For reasons of space, structure and economical use of coolant, for instance, the cryostat vessel walls may conform somewhat to the outer coil shape. Furthermore, the design of the cryostat will depend largely on the type of cooling chosen. Uchikawa identifies several methods:

"1. Pool boiling of liquid helium,
2. cooling by superfluid helium (He-II),
3. forced circulation of supercritical helium,
4. forced circulation of subcooled helium,
5. forced circulation of two-phase helium"[35],

Of the five cooling methods, pool boiling is the

simplest. As its name suggests, the superconducting coils are essentially "dunked" in LHe, which dissipates magnet heat by boiling. The cryostat in this case is little more than a very well insulated tank, which, as will be seen, is complicated enough. Pool boiling has disadvantages for large magnets, however. These coils need cooling channels to keep the temperature uniform over the cross section, and the larger the magnet, the longer the cooling channels. If the channels get too long, bubbles formed by the boiling helium may not escape readily. The result can be insufficient cooling in the vicinity of the trapped bubble and the formation of a local normal region in the magnet.

The various forms of forced flow cooling involve complicating the cryostat system somewhat, in order to accommodate pumping equipment, but they do overcome the problem of trapped bubbles and thus have superior heat transfer characteristics compared to pool boiling. The use of He II entails very complicated cryostats, and places a heavy burden on the refrigeration system, since helium becomes superfluid only at 2.3°K. These considerations probably override the advantages of higher heat transfer and better magnet characteristics resulting from the lower temperature. From an accessibility standpoint, then, the simpler dewar arrangements that suffice for pool boiling and forced circulation of normal helium are far preferable.

A common dewar implies a common dewar wall, a structure which is quite complex. Even the simplest LHe cryostat will have inner and outer walls, and between them, superinsulation, a vacuum space and cooling channels, for a thickness amounting to approximately 20 cm. A double superinsulated cryostat, with a second vacuum space, would, of course, be thicker still, and the addition of an intermediate LN_2 cryostat, even more so. The purpose of the added superinsulation and/or the LN_2 cryostat is to reduce the LHe loss due to room temperature radiation, but, if used, they greatly complicate the task of accessing the inner reactor. Demountable seals for such an arrangement would have to be vacuum tight (to about 10^{-4} torr) as well as thermally insulating. The design of such a seal would itself be quite complicated, and none are known to exist. To get through the dewar to the reactor, therefore, would entail:

1. Draining all cryogenic fluids from the dewar(s);
2. warming up all superconducting magnets to room temperature;
3. Cutting through walls, coolant tubes, vacuum space and insulation, without harming the coils inside.

Furthermore, all this damage will have to be repaired be-

bore starting the reactor up again. The process is time-consuming, wasteful and expensive.

Unless a method is developed for demountably sealing a helium cryostat, no fusion reactor, whatever its geometry, can be truly modular if all of its superconducting magnets share a common dewar. There is really no choice, however, with some designs, notably stellarators with continuous helical windings, such as Wistor and MIT's Torex-4; continuous coils imply a common dewar. An alternative available to discrete coil designs is individual dewars, or at least a dewar common to as many magnet coils as are to be included in one module. MFTF, for example, has a central cell comprising seven modules, each containing two of the 14 central cell solenoids. Both magnets in a pair share most appurtenances, including the cryostat. Stellarators with discrete coils are also likely to have more than one to a module, because the aspect ratio and number of coils are both large. Tokamaks, on account of their small aspect ratios and comparatively few (16 or so) large coils, will almost certainly be divided so that each module features one TF coil. The term "individual dewars" then is to be taken to mean "one dewar per module".

Individual dewars represent a considerable improvement in accessibility, at least to parts of the reactor other than the coils themselves. Even if some of the coils must be reached, it is only their dewars which must be opened;

the others can remain intact. Individual cryostats also permit coils not involved in a repair or maintenance operation to be kept cool, if not at LHe temperatures, then perhaps at LN_2 temperatures, about 80°K. This reduces thermal cycling and stresses, and lessens the demand on the refrigeration system, since it will not have to take on the task of cooling down all coils from room temperature once reactor startup is desired.

Individual cryostats have disadvantages, too. A common dewar, though it may be bulky, is not too sensitive to the distance between coils, since it needs no walls of its own between them. Individual cryostats, of course, do need them, and if the magnets are closely spaced, as in modular stellarators, the space can get quite crowded. The problem can be reduced somewhat if it is observed that walls between adjacent cryostats do not need to be thermally isolated as much as walls that face a 300°K environment. They can thus be made considerably thinner. When one module is retracted, and it is desired that the coils in adjoining modules be kept cool, insulation can be affixed to them after the module is removed. Thus, though the dewars are individual, where they are adjacent walls they do not have to be thermally isolated from one another.

The concept of individual dewars with thin adjacent walls can be realized partially where feasible, as in toka-

maks, where the inner edges of the TF coils are close together, but the outer edges are far apart. A schematic of this idea is given in Figure 12. Tightly packed coils evidently will not present an insurmountable problem for purposes of cooling.

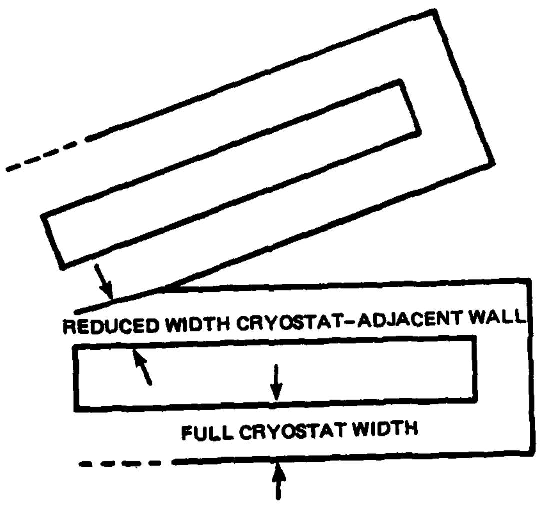


Figure 12. Individual Cryostats with Adjacent Walls.

CHAPTER 4. MAGNETS

The fundamental difference underlying all three types of reactor under consideration is the configuration of the magnetic field confining the plasma. The field is typically produced by large superconducting magnet coils, which generate the overall, grossly confining field, and by other, smaller, often normally conducting magnets, which serve to give refining or correcting fields. The nonsuperconducting, or normally conducting magnets will be discussed first.

4.1 Normally-Conducting Magnets

Besides constituting in experiments to date the majority of magnets whose counterparts in commercial reactors will be superconducting, normally conducting magnets have a permanent place in the scheme of fusion power. Their share in fusion literature is significantly smaller, probably because they present less of a problem. Most of the technology of normally conducting magnets is mature and well-known. They are usually smaller than their companion superconducting magnets (SCM's), they are simpler, produce lower fields, need less exotic cooling, are composed of more fault-tolerant materials and are sturdier. Typical examples of coils which are frequently (not always) normal are tokamak PF coils and torsatron vertical field (VF) coils, which, in appearance if not in function, are quite similar. For reasons of space, torsatron VF coils are almost certain to be located outside the superconducting helical

windings, whereas tokamak PF coils will be found both within and without the bore of the TF coils. From the standpoint of modularity and accessibility, therefore, the PF coils are all that need to be considered.

A PF coil will probably weigh only a fraction of what a TF coil weighs, tens of tons instead of hundreds of tons. Since they are relatively simple in construction, and because they are resistive coils in the first place, the addition of demountable joints for the purpose of modularization is straightforward. The joints must, of course, be amenable to easy, and possibly remote, assembly and disassembly, and must not degrade the mechanical integrity of the coil. But there is no question of their being incompatible with the coil operation and function.

Figure 13 shows three different positions for PF coils, of which two, "A" and "C", could be positions for VF coils on a torsatron. The coil at "A" is the easiest to deal with. It is out of the way of most reactor components; it can be readily suspended from the reactor room ceiling, thus taking up no precious floor space; many maintenance and repair operations on it can be done in situ; it is easy to get at; and it can be made demountable independently of main reactor modules. For example, even if the reactor as a whole is made up of 16 modules, ease of movement of this PF coil may only require that it be broken up into four segments. A four-part coil is easier

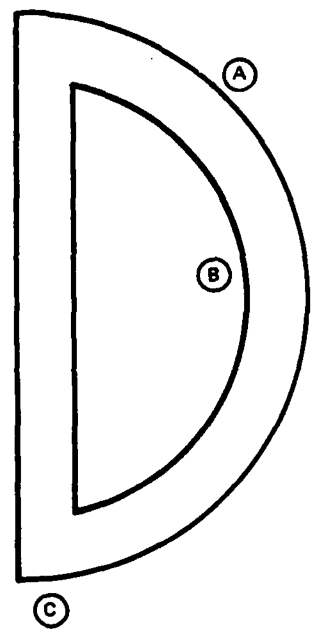


Figure 13. Possible Locations for PF Coils.

and cheaper to maintain, more reliable and less expensive than one of 16 parts. Yet, if one of the reactor modules must be retracted, the quarter-PF coil in its way can be moved almost as easily as if it were a 1/16 part.

The coil at location "C" will be somewhat harder to handle. Situated underneath the TF coils, it is located behind a large amount of support structure. Minor in situ operations on it may be possible, but anything major will require that it be segmented so that each segment forms part of a main reactor module. Even with its module retracted, though the PF coil section will not be immediately accessible. To get at it, it must either be pulled out of the module, which means that it must be originally mounted so as to make this easy (for example, on a rolling dolly); or the support structure in front of it must be cut away, meaning that alternate temporary support for the module must be put in place. Thus, the problem here is not with modularizing the PF coil as such, which seems to be relatively easy, but in arranging the main reactor module.

Location "B" is inside the bore of the TF coils. It has been seen that the space between the TF coils is limited, and that even when individual dewars are employed, they are likely to fill nearly all of this space, hiding even those parts of the PF coil that do not fall directly in the shadow of a TF coil. Access to the PF coil can

consequently be gained only by either breaking through a TF coil, which entails cutting through its structure, dewar and coil case; or by retracting the reactor module, which breaks the secondary vacuum of 10^{-8} torr and exposes the radioactive first wall and blanket region. If the latter course of action is taken, the problem of accessing the coil from within its module, which occurs with location "C", crops up here as well. At any rate, the PF coil at location "B", since it must be situated within the reactor modules, must itself be part of them, and hence modular itself, segmented into at least as many parts as the reactor as a whole.

4.2 Characteristics of Superconducting Magnets

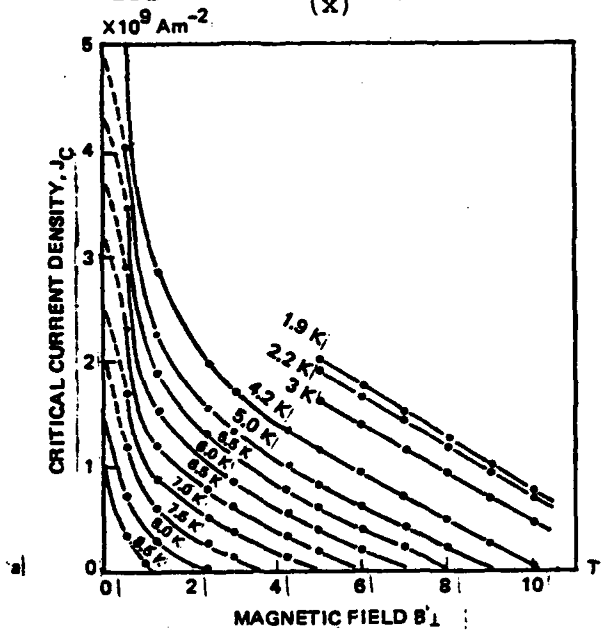
Superconducting magnets are complex, delicate, expensive and require an extreme operating environment. In fusion SCM's, these characteristics are compounded by their sheer size, and in some cases, such as mirror machine yin-yang coils, by a complicated shape. What are the motives for using them in lieu of less troublesome normally-conducting coils? The answer is primarily that only superconductors can produce, at least economically, B-fields of the magnitude demanded for most fusion reactors, from six to 12 tesla or more. Though in principle much the same as present SCM's, the large magnets for fusion systems, because of their size and weight, are beyond the

current state of the art.

Superconducting material constitutes only a small portion of an SCM. The bulk of the magnet is composed of a highly conductive stabilizer, and there are usually insulating materials, coolant channels, and strength members included as well. The need for insulation, strength members and cooling channels is largely self-explanatory, but the purpose of the stabilizer deserves some discussion. The high current densities of fusion SCM's, on the order of several thousand A/cm^2, necessitates employing the superconductor in the form of very fine filaments, typically less than 0.1mm. The stabilizer serves as a matrix to hold the filaments in the desired configuration. Furthermore, it carries the current when and if the superconductor, for whatever reason, becomes resistive, thus helping to prevent overheating of the magnet.

Many materials can be made superconducting, but research and development on SCM's for fusion has concentrated almost exclusively on two: niobium-titanium (NbTi) and niobium-tin (Nb_3Sn). The maximum current density J and maximum magnetic flux density B are functions of temperature; usually, the lower the temperature, the higher the limits on J and/or B. Figures 14 and 15 show these interdependencies for NbTi and Nb_3Sn. It can be seen from

Figure 14. Temperature Dependence of Critical Current Density Versus Applied Transverse Magnetic Field for $Nb_{(x)}Ti$.[36]



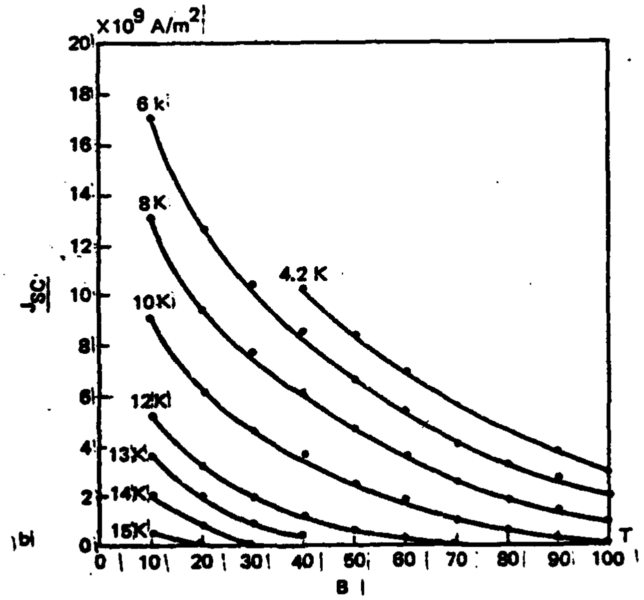


Figure 15. Temperature Dependence of Critical Current Density versus Applied Transverse Magnetic Field for Nb_3Sn.[37]

these figures that for a given current density and temperature, Nb_3Sn has a higher critical field than NbTi. For reasons of safety and reliability, it is desirable to operate coils at well below critical field, and, therefore, in high field applications, Nb_3Sn is the preferable of the two. Predictably, though, there are disadvantages to its use. Industry experience with NbTi is far more extensive than that with Nb_3Sn, and the latter is very brittle (allowable strain is only 0.2%), difficult to handle and results from a more involved manufacturing process. NbTi is an alloy, produced by melting the two metals together, whereas Nb_3Sn is obtained from the solid diffusion of tin into niobium. The diffusion process takes place only after the coil has been fabricated, and requires many hours, sometimes days, at high temperature. This has the effect of, among other things, annealing most materials which can be used as strength members. For example, copper, which is the most frequently used stabilizer, must often double as a load-bearing agent, and annealing degrades the strength gained through working it. For these reasons, NbTi is nearly always preferred wherever the desired field is low enough to feasibly use it. In fact, coil designers and manufacturers are so partial to NbTi, that research is underway to develop methods of[7] splicing NbTi and Nb_3Sn superconductor together in one

magnet, so that use of Nb_3Sn can be abandoned on those parts of the magnet where it is not otherwise needed.

4.3 Modularizing Superconducting Magnets

As mentioned in the previous section, SCM's are not constructed out of big homogeneous blocks of material, but are rather built up from braids, cables or tapes of stabilizer impregnated with supconducting filaments. The strands are arranged around strength members, cooling channels and whatever other components are necessary to the coil design. Thus, even a "unitary" or non-modular coil is not really made in one piece, but is a composite of many different elements. One composite configuration is depicted in Figure 16. The complex construction of SCM's is a feature which will figure heavily in the discussion of magnet reliability.

The size, weight, complexity, delicacy and relative inaccessibility of fusion SCM's make most designers unwilling, or at least reluctant, to provide for taking the things apart once they are placed in the reactor. But there are a number of scenarios in which it would be desirable to remove only a part of an SCM, such as gaining access to a portion of the reactor which lies between the coils or windings and the blanket region. Examples would be repairing the inside wall of a magnet dewar, or, in a tokamak, maintenance of an internal PF coil. In cases

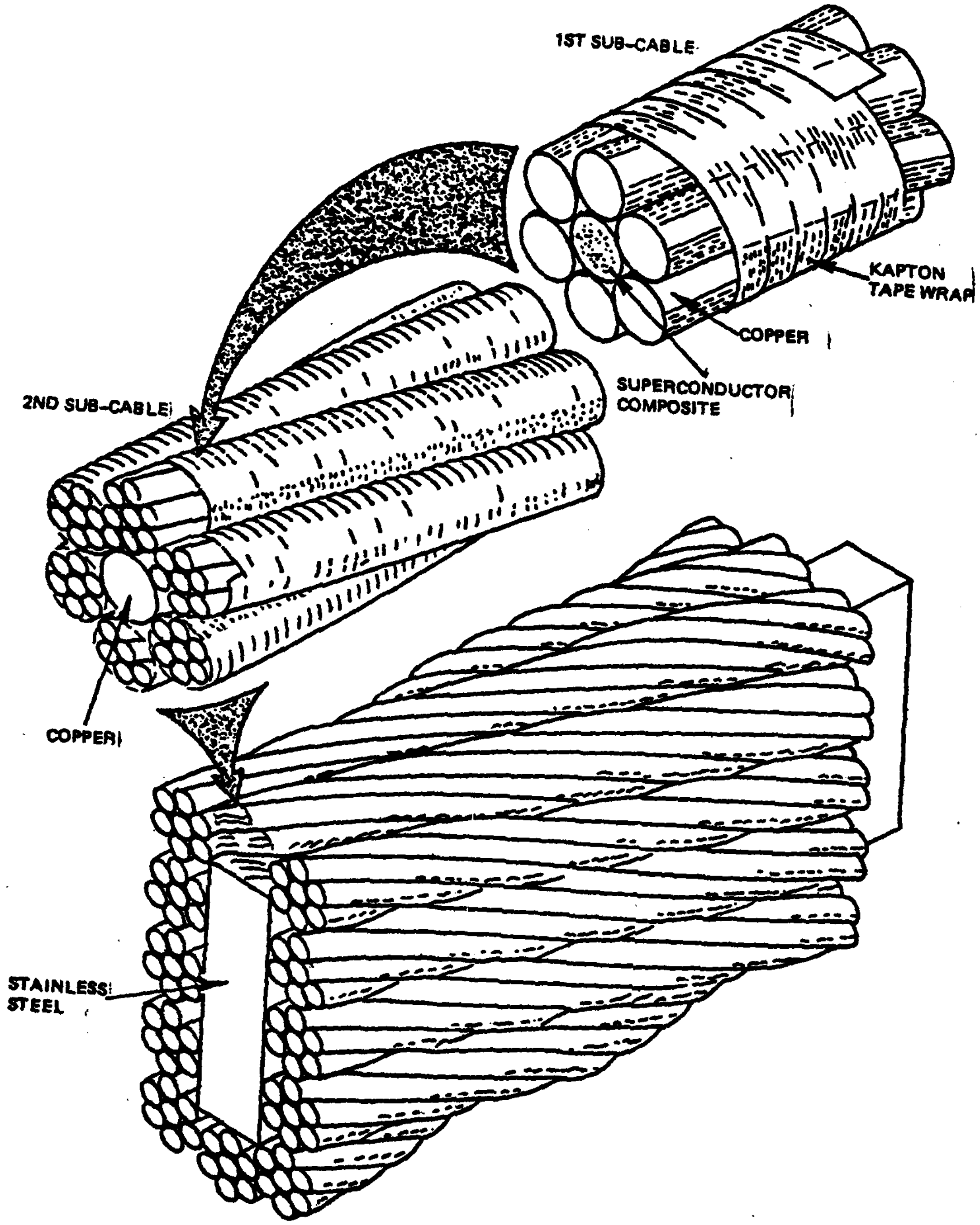


Figure 16. Reinforced Braid Conductor.[38]

like these, it might be possible to avert the need to retract an entire reactor module, which would expose the radioactive plasma chamber, if a portion of the helical windings or part of a TF coil can be removed. Another reason that modular SCM's may be desirable is the replacement of a part of a magnet that has deformed, broken, melted or otherwise become unfit for continued operation. Replacing part of a tandem mirror demountable yin-yang coil, for example, would probably be preferable to replacing the entire thing.

Having observed circumstances in which it would be desirable to take apart an SCM, it remains to be asked how feasible it is, that is, can it be done safely, reliably and economically? Hardly anyone would suggest that cutting into the superconductor itself would be an attractive solution, and certainly not for routine maintenance. Such a procedure may have to be done, of course, but it is generally regarded as a last resort operation in the face of some catastrophe. Thus, when a unitary magnet is designed, it is intended to remain intact for the lifetime of the plant.

Permanent joints in superconductors have been around for some time, and can be formed by methods like cold welding, diffusion welding, soft soldering, explosion bonding or ultrasonic joining. They are invariably resistive,

but with resistances ranging from about 10^{-7} ohms down to 10^{-16} ohms. The lower end of the scale is very difficult to achieve, but even at the high end, the reistance should not cause too much trouble. A $10^{-8}\Omega$ joint in a 10^4 A conductor will produce only a watt of heat. Practicality may dictate putting up with several such joints in a unitary magnet even if the state of the art permitted the magnet to be made without them. This is because the bulk and weight of a magnet can obviously be more easily shipped and handled if it is made in several pieces and put together later, even on-site.

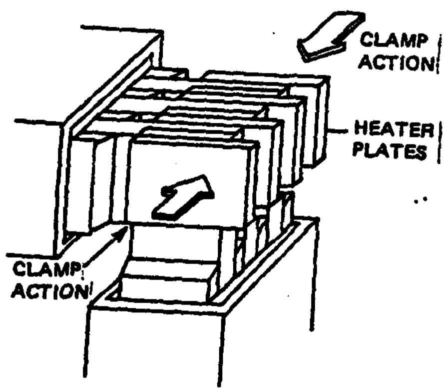
Permanent joints, however, are not the answer to the problem of how to take apart SCM's. What is required is a demountable joint that is economical, easy to make and operate, of low resistance, durable and reliable. Designs for such joints appear to be feasible, and some are possibly within the state of the art. Conceputal designs or design guidelines for demountable joints for both tokamak TF coils and torsatron helical windings have been proposed, with possible transferrability to tandem mirror solenoids (there appears to be little incentive to provide for disassembly of baseball or yin-yang type magnets, desirable though this would be, first, because of their complicated shape, which would involve large amounts of joint support, and second, because they are not much in the way

there is an additional advantage: "Brittle superconductors can be readily used since strain is minimized and conductors do not have to be wound when the coil is assembled. Also, superconductors fabricated by sputtering, vapor deposition, etc., techniques can be used".[41] Features of the DEALS magnet designed for a UWMAK-II sized reactor are summarized in Table 4. The DEALS magnet has some disadvantages. The authors mention the heat leak rate arising from the resistive joints, and the current on the order of 10^5A, about ten times that of conventional TF coil designs. Moreoever, the toriodal field produced by a set of rectangular coils may not be optimum from a physics standpoint. There is little doubt that a magnet of such relatively simple construction and easily demountable joints is far easier to maintain and replace than one of unitary construction (the sacrifice in reliability occasioned by the segmentation is almost surely overwhelmed by the shorter turnaround time for a failed coil). The authors' estimate of only a month to repair seems to be pretty close. Routine procedures usually specify from five days to a week to simply warm up the coil, although in an emergency it could be done in a few hours. E. Toyota, et al[42] estimate eleven days time to get to the TF coil. Depending on which segment is to be replaced, the removal and replacement operation could take

of anything else in the reactor). J. Powell, et al, suggest a design for a demountable tokamak TF coil. The coil is rectangular, comprising four pieces joined by four 90° joints (see Fig. 17). The internal surfaces of the joint are pretinned and clamped together with a heater plate inserted. When the heater plate is turned on, the surfaces of the joint solder, and after cooling the clamps can be removed. The authors summarize the advantages of the rectangular TF coil:

> A segmented rectangular TF coil...has several significant advantages over a segmented curved coil:
>
> 1. ease of segment manufacturing and shipping;
> 2. ease of removal and insertion of both failed and new segments (only a straight pullout or insertion of a segment is required);
> 3. use of massive conductors and insulators is readily accommodated (joining and disjoining is easier of relatively few turns are used).[39]

If the reinforcement structure of the segmented coil is mostly at room temperature, the magnet can be a DEALS (Demountable Externally Anchored Low Stress) magnet. This type of design requires features that: 1) keep the coil rigid, such as plate-type conductors and insulators and a rigid coil case; and 2) reduce stress in the coil, such as external supports. Minimizing stress in large, complex, dynamic structures is always a good thing, but in SCM's



(1) INSULATED CLAMP APPLIED TO THE JOINT TO MAKE GOOD CONTACT BETWEEN CONDUCTOR TINNED SURFACES AND ALSO THE HEATER PLATES.

(2) WHEN PROPER SOLDERING ACTION IS FINISHED, HEATER IS TURNED OFF WITH CLAMP ON.

(3) CLAMP AND HEATERS ARE REMOVED WHEN THE JOINT RETURNS TO ROOM TEMPERATURE.

Figure 17. DEALS Magnet Joint.[40]

TABLE 4

FEATURES OF A DEALS MAGNET FOR A UWMAK-II SIZED REACTOR

Length of Vertical Leg	30 m
Length of Horizontal Leg	20 m
Width of Conductor	1 m
Thickness of Conductor	1 cm
Thickness of Coil Case	12.7 cm
Conductor Current	$\sim 10^5$ A
Type of Joint	90° demountable soldered
Refrigeration Requirements	16.6 MW
Maximum wtress in Coil Case	1.4×10^4 psi
Maximum Stress in Supports	3.1×10^4 psi
Maximum Stress in Conductor	10^4 psi

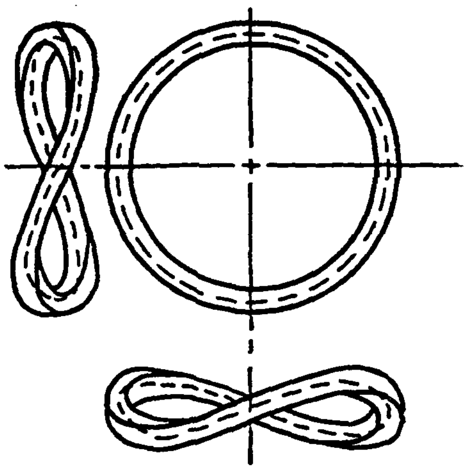
from two to perhaps five days. Lastly, it is likely to take two weeks to put back together what took eleven days to take apart, so the entire operation should consume in the neighborhood of five to six weeks. The McDonnell Douglas study estimates a downtime of 40 days, which agrees with the above estimate. A summary of the 36-step procedure outlined in the study for ther removal of a segment is given in Appendix A. By contrast, the mean time to repair or replace (MTTR) in the case of unitary TF coils is usually estimated to be one and one-half to three years.

Modularization of stellarator windings can take on several forms, and attention will be focussed here especially on torsatron windings. In the literature a modular torsatron is usually one in which continuous windings give way to discrete coils which carry the winding law, and these coils are often deformed in or out of their own plane. They present, from an access point of view, a tremendous improvement over continuous, nonmodular helical windings, and they have several physics advantages as well. T.K. Chu, et al, observe: "...modular coils can offer a wide range of vacuum magnetic field configurations, some of which cannot be obtained with the classical stellarator or torsatron coil configuration."[37] Furthermore, "A modular stellarator...has lower edge transform and more usable magnetic volume than a classical stellarator."[38] Various deformations from a planar circle are possible. Planar

ellipses can be used for $\ell = 2$, planar triangles $\ell = 3$. Nonplanar coils can also be used, though their fabrication will be more difficult. Figures 18 and 19 show nonplanar circular coils for $\ell = 2$ and $\ell = 3$.

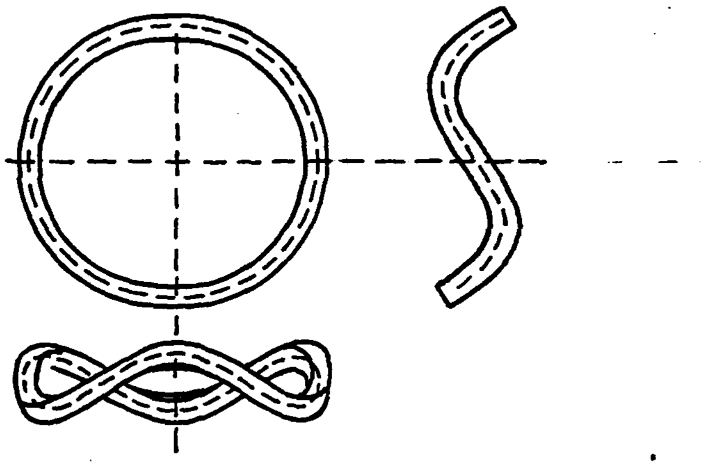
In most reactor concepts, physics considerations call for many coils tightly packed togehter, whereas considerations of maintainability make few, widely spaced coils preferrable. The physics considerations seem to have won out in many modular torsatron designs. These designs specify 50 or 60 coils, as opposed to typical tokamak designs, which normlly have fewer than 20 TF coils. Thus, modular torsatron magnets are rather tighly squeezed in, negating some of the advantages of a high aspect ratio. One method of alleviating the problem would be DEALS type joints, but in the case of coils that are distorted in the toroidal direction, the joints would have to be very carefully placed.

Classically continuous windings are another alternative to unitary stellarator coils. The continuous windings can be modularized in a number of ways, usually involving separating them in the reactor major radial direction rather than somehow untwisting the helices. One method is the use of crossover turns at both ends of each windings module, a scheme which requires considerable reinforcement to counter coil stresses. Another is de-



$\ell = 2$ COIL

Figure 18 [45]



$\ell = 3$ COIL

Figure 19 [46]

mountable joints. The interlocking fingers type of joint used for DEALS would be inappropriate for continuous helical windings, which contain no sudden discontinuous changes in shape. J.M. Noterdaeme, et al describe a series of experiments done to help determine the feasibility of demountable joints for torsatron superconductors, and remark:

> Several features make the Torsatron a more likely candidate for application of demountable joints than the tokamak. Primary of these is the low bending nature of the Torsatron windings. The proper pitch angle for the windings result in a nearly force-free state for the helical windings, that is the field at the windings is nearly parallel to the current flow. The demountable joints are thus not subjected to bending under normal operating conditions. Secondly, the Torsatron is a large aspect ratio device, allowing ample approach space to the windings from all sides. Lastly, the Torsatron is a steady state device and, therefore, relatively free from cycling and potential fatigue degradation of joints.[45]

The type of joint chosen for the study was an overlap joint, clamped but not soldered, and the superconductor chosen was NbTi, a material suitable for the maximum flux density of 8.7 T of the T-1 Torsatron. Joint resistance ranged from $5.1 \times 10^{-10}\Omega$ for a silver-plated joint to $9.8 \times 10^{-8}\Omega$ for a copper oxidized one. The sizes of the joints and the current used were by no means meant to simulate reactor parameters, and were in fact orders of magnitude smaller. The T-1 reactor design calls for conductor carrying a current of 5×10^{5}A, a significant extrapolation

of the state of the art. A T-1 size reactor with 9000 joints, each 3200 cm^2 in area would require a contact resistanc of less than $6 \times 10^{-8} \Omega\ cm^2$ to keep refrigeration demand below 1% of the 4340 MW_t output. Some of the experimental size joints in the study had contact resistances about 30 times less than that. One conceptual design for a 5×10^5A jiont has been calculated to dissipate 0.6 w/cm^2; 9000 of these 3200 cm^2 joints would dissipate about 17.3 MW, well within the 1% limit. Hence, while not yet possible under current practice, joints of this type show considerable promise for future systems.

4.4 Downtime and Reliability

The necessity of ensuring that fusion reactors be compatible with commerical power generation requirements has been repeatedly emphasized, particularly as regards accessibility and ease of removal and replacement of components. These factors have been stressed because of their crucial role in reducing both scheduled and unscheduled downtime and increasing availability. Another way to reduce unscheduled downtime is to increase the reliability of the reactor components, reliability being defined as the percentage of time that a component works correctly divided by the total amount of time that it is in demand. If all reactor components were 100% reliable, that is, if

they all worked exactly as desired all the time, there would be no unscheduled downtime. In fact, of course, things do often malfunction or break, even in mature, well-established technologies and simple equipment. In most cases, the maximum reliability possible to the state of the art is not actually incorporated into a system because of expense; beyond a certain point, increasingly large amounts of money buy increasingly smaller increments of reliability. When the technology in question is relatively new, like SCM's, which have only been around for about 20 years, the problem is not only figuring out how often, based on short experience, a given type of failure will occur, but what kinds of failures can occur. Even the most careful designer cannot foresee all of the ways and places that failures can happen, and which will reveal themselves only through experience. Hence, the overall policy in the fusion community of taking small steps in advancing the state of the art.

Two principal ways to achieve a desired reliability are quality assurance and redundancy. Quality assurance, as its name suggests, means good design and a system built to that design, in the proper manner with the proper materials. Inspection, testing (including destructive testing on samples), monitoring and preventive maintenance all form part of the process, beginning with the preliminary design and continuing through the life of the component.

Appropriate techniques for monitoring and detecting possible failures are crucial, because early detection can often mean the difference between a minor problem that can be corrected in situ and a major failure requiring extensive downtime and cost.

Redundancy is harder to achieve in a superconducting magnet system of the size considered here. Backup central cell solenoids, TF coils or helical windings, placed but inoperative in a reactor, and ready to take over in the event of a primary coil failure, are probably not feasible, still less backup transition or barrier coils for tandem mirrors. For one thing, they probably would not fit, and for another, the cost would almost certainly be prohibitive. It is asking a lot already to have an entire extra reactor module sitting in some "back room" to replace one that malfunctions during operation. Under certain conditions, though, some in situ redundancy may be possible, extra PF coils in some locations in a tokamak, for example, or redundant stellarator VF coils. A certain amount of redundancy can be incorporated into some kinds of SCM's in the form of extra capacity. In SCM's built of layers of pancake windings, for example, more pancakes than are needed to produce the required field can be included, so that in the event of a pancake failing for some reason, it can be electrically isolated and shut off without

the performance of the coil being degraded below reactor requirements. If this can be done remotely, say through a simple switching mechanism, unscheduled downtime from a failed pancake can be minimized, and access to the coil itself may not be necessary.

How often can a large SCM be expected to fail in such a way as to necessitate replacement or extensive repair of the magnet? Judging from the assumptions made in many extant fusion system designs, including imminent experiments, the answer would seem to be almost never. The failure rate assigned to the MFTF-B magnet system is 10^{-6} per magnet per year. This does not include accidental quenches that do no damage, or other nondestructive problems with the coils, but by any measure, this is an extremely small number, and justification for it is scanty. In fact, justification for most reliability figures on SCM's is difficult to come by because:

1. The total operating experience with SCM's is 100,000 to 150,000 hours, or 11 to 17 years, not enough to confidently predict failure rates, especially rates as low as those deemed acceptable by the fusion community.

2. The total operating experience with fusion-size SCM's is nearly nonexistent. Failures related to scale and complexity are bound to crop up, but have not yet had a chance to do so.

3. A thorough qualitative fault-tree type of analysis on superconducting systems has not yet been done. A comprehensive quantitative fault-tree analysis, of the magnitude of WASH-1400, is even further in the future.

Setting reliability criteria through availability goals is an accepted practice. Suppose, for example, an availability goal of 80% in a system comprising ten components and having an expected lifetime of 20 years, and that each time a component breaks down, it takes 0.01 years to fix it on the average. The total permissible downtime is four years, which allows 400 breakdowns. Then if the failure rate is designated as F,

$$F = 400 \text{ failures} \times \frac{1}{10 \text{ components}} \times \frac{1}{20 \text{ years}}, \qquad (4)$$

$$= 2 \text{ failures per component per year.}$$

Component design and/or procurement could then proceeed with this failure rate in mind. The example is greatly oversimplified, of course; most systems have more than ten components, which are not likely all to have the same failure rate or MTTR, but the principle is evident. For fusion plants, assuming typical industry availability requirements and nondemountable TF coils having replacement times from 3 to 30 years, the required failure rate is 10^{-3} - 10^{-4} per coil per year.

Now, it is one thing to need a failure rate no more

than 10^{-4} per coil per year, and quite another thing to actually have it. What can go wrong with SCM's? To put it bluntly, plenty of things, some of which have already happened. The history of SCM failure experience up to 1977 was reviewed by S.Y. Hsieh, et al, and the results are summarized in Table 5. The authors point out that," ... more than 50% of the existing superconducting magnet systems, which are simpler and technologically less demanding than CTR reactor magnets, have had failure experiences."[46] Thus, a lower limit on the failure rate, assuming that all SCM's have operated for 17 years (which they have not), is 0.5/17 years, or 0.03 failures per year. The true figure is certainly higher than that, perhaps by an order of magnitude. Yet, even this lower limit figure is orders of magnitude higher than what is considered acceptable. Furthermore, the experience in question, as pointed out in the above quotation, is on magnets that have placed on them nowhere near the demands tc be placed on fusion reactor magnets. Most of the magnet systems listed in Table 5 store energy that is orders of magnitude less, produce far smaller fields and are themselves much smaller than CTR magnets.

J. Powell, et al, observe:

TABLE 5

FAILURES IN SUPERCONDUCTING MAGNET SYSTEMS

Magnet	Field (kG)	Stored Energy (MJ)	Failure
PNAL Prototype Energy Doubler C10-3	40	0.15	Powering circuit shortened shunt, energy dumped internally, causing hot spots of >400°K. Irreparable.
LBL Beam Transport System	42	0.7	Short between windings caused arcing. Energy dissipated internally. Coil repaired.
NASA Bumpy Torus Magnet System	30	0.6	Deterioration of Shunt and insulation blocked cooling passage, causing arcing which melted lead wires. Repaired.
NASA SUMMA Magnet System	88	18	Insufficient electrical insulation and mechanical support permitted arcing and shorts between pancakes
			Power lead overheated due to insufficient cooling. Operational, but power degraded.

(cont'd)

Magnet	Field (kG)	Stored Energy (MJ)	Failure
Princeton University 3-section solenoid	--	--	Power lead failed due to insufficient coolant flow, apparently causing hot spots and arcing. No longer in use.
Princeton University IGC solenoid insert	55	0.1	A lead wire melted open during a quench, possibly due to insufficient cooling. Possible too that wrong material used for shunt-terminal connection
Rutherford Laboratory Prototype Synchrotron Magnet AC3	40	60	A current feed broke off a full current, causing arcing. Magnet coil undamaged, perhaps because of many protection and detection devices.
RCBC Magnet	20	1.2	Blockage in coolant channel led to insufficient cooling of coil connecting wire, which melted. Coil arced to ground. Repaired.
BNL 8° Beam Transport Magnet System	40	0.3	Overheated gas-cooled power lead caused arcing. Unit repaired.

(cont'd)

Magnet	Field (kG)	Stored Energy (MJ)	Failure
BNL 7-foot Bubble Chamber Magnet	30	61	Inadequate instrumentation failed to detect insufficient coolant flow, resulting in burned power lead. Repaired.
mit Alternator Magnet	25	90	Inadequate cooling of lead, and insufficient Cu stabilizer resulted in partial evaporation of lead. Coil arced to ground, damaging itself and dewar. Repaired.
McGill University High-Field Solenoid	150	4	Inadequate mechanical support led to inner coil distortion and arcing in outer coil. Repaired, but performance degraded.
Princeton University 60" Levitated Ring	28	0.3	Inadequate mechanical support led to severe conductor movement. Ring had to be replaced. Eventually repaired.
MIT Hybrid Magnet Coil	200	2	Poor quality conductor led to successively worse performance each time operated. Had to be rewound.

> ...the time between failures for TF magnets will have to be considerably longer than the accumulated operating time on the relatively simple superconducting systems that have been built to date.
>
> Consequently, it does not seem possible to base predictions about the safety and reliability of future CTR magnet systems on experience with existing superconducting magnet systems...Such predictions have to be based on analytical methods for a considerable time to come.[48]

The analytical methods referred to include such reliability techniques as fault trees, event trees and failure modes and effects analyses (FMEA's). The set of FMEA's alone for the MFTF magnet system occupies over 70 pages. The types of failures treated are summarized in Table 6. Appendix B shows the MFTF magnet system fault tree.

The hopes for SCM failure rates of 10^{-4} per year per coil, therefore, seem far too optimistic, at least until considerable experience, on the order of millions of hours at the minimum, with actual fusion reactor size SCM's has been accumulated, and this will not occur for many decades. Until then, the fusion community should consider more seriously than it has to date the possibility of using demountable SCM's, whose replacement time is weeks rather than years. To be sure, the addition of extra complications to systems already highly complex may

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TRADEOFFS IN THE MODULARIZATION OF LARGE FUSION SYSTEMS.(U)
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2 of 2

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TABLE 6

FAILURES TREATED IN MFTF FMEA'S

1. Magnet Coil
   a. Shorted turn
   b. Short between two layers
   c. Ground fault
   d. Open conductor or joint
   e. A section of conductor has low critical current
   f. Restricted cooling passage
2. Current Leads
   a. Open circuit
   b. Ground fault
   c. Short circuit between conductors
   d. Heater fails
   e. Solenoid bypass valves fail
   f. Helium gas flow is too high
   g. Helium gas flow is too low
3. Liquid-Nitrogen Liners
   a. Liquid nitrogen leak
   b. Loss of flow through liners
   c. Panel or pipe touches magnet case
   d. Thermal emissivity is too high

(cont'd)

Table 6 (cont'd)

4. Guard Vacuum
    a. Vacuum pump fails
    b. Line leaks
5. Magnet Case
    a. Coil structure deflected excessively
6. Magnet Supports
    a. Support failed in tension
7. Power Supply and Protection System
    a. Utility power failure
    b. LCW failure
    c. Power supply failure
    d. Bypass switches fail
    e. Slow dump switches fail
    f. DC circuit breaker fails
    g. Failed joint
    h. Short circuit between vault cables
    i. Ground fault
    j. Open circuit of cable bus
    k. Dump resistor element fails open
    l. Dump resistor short circuit
    m. Battery voltage is too low
    n. Inverter fails
    o. Fast dump control circuits fail
    p. Programmable controller fails
    q. Battery system fails

(cont'd)

Table 6 (cont'd)

8. Cryogenic System

    a. Liquid nitrogen flow stopped

    b. Helium refrigeration system fails

    c. Dewar supply and return valves fail closed

    d. Dewar vent valve fails open

    e. Dewar vent valve fails closed

    f. Helium gas valves fail open

    g. Liquid helium line breaks

    h. Utility power lost to cryogenic system

    i. Compressed air lost to cryogenic sytem

    j. Helium temperature too high

    k. Nitrogen temperature too high

    l. Nitrogen flow rate too low

9. Vacuum, Vessel Systems

    a. Influx of air onto magnet surface

    b. Vesselpressure exceeds 10^{-6} torr

10. SCDS, LCIS

    a. Control not functional from control room

    b. Monitoring not functional at control room

be seen as an enormous headache. But it appears to be not a luxury but a necessity, and far less of a headache than a failed nondemountable coil in a commercial reactor.

CHAPTER 5. REMOTE HANDLING

5.1 Overview

When E. Kintner represented the challenges to be overcome by the magnetic fusion program, he compared them to successively deeper levels in a Dantian type hell. The ninth and deepest level, where Satan resides, he assigned to maintainability, and remarked:

> The maintenance philosophy shown in early reactor plant designs reminded me of the "deus ex machina" device of the ancient Greek plays--when Greek playrights had written their characters into impossible situations, the Gods were always called in to extricate the protagonists by miraculous means. Our studies have in the past used the same technique, only we labeled it "Remote Handling". It was always pictured as some undefined super machine off to the side.[49]

There is, to be sure, some excuse for this. A major fraction of fusion research has been dedicated to proving scientific feasibility of the concept itself. Obviously, if the physics prevented us from having fusion reactors, no one would much care whether or not the impossible machines could be maintained. But with increasing optimism for proof of scientific feasibility, as well as increasingly reactor-like experiments being built, the maintainability problems, and with it remote handling, have had to be squarely faced.

First, it may be asked what constitute the primary

features and requirements of remote handling. P. Sager, et al, in a report on a remote maintenance equipment workshope, divide the principal features into three areas: transporters, viewing systems and manipulators.[50] Of the three, transporters are probably the most satisfactorily developed to date. Movement of big, heavy and delicate things is a common phenomenon in industry, and little modification will be needed to accommodate fusion reactors. The development of the necessary viewing systems is not as far along. They will be either premanently placed within the reactor or brought in for a given task. Those located permanently in the reactor will compete for space which already has many claims on it, will have to withstand a severe environment in many cases and will have to be strategically placed, mobile if possible. Thus, they must be small, sturdy and versatile. The use of optical fibers to extend the viewing capabilities of the system will almost certainly be necessary.

Of the three classes of remote equipment, though, the one that perhaps has the greatest aura of "deus ex machina" about it is manipulators. Working manipulator designs have not changed radically since the fifties, so development in this area lags far behind the technology that could be applied to it. A team of expert designers could probably, using existing technology, design a remote handling system suitable for CTR maintenance and repair. No such system

does, in fact, exist, however, nor anything like it. In order for one to be properly designed, moreover, the remote equipment designers must be in on the planning for the particular reactor from the very beginning. Retrofitting an existing design, in which scientific and engineering tradeoffs have in places been pushed to an extreme, and in which most parameters and components have been "set in concrete", would be nearly, if not completely, impossible. In the past, CTR designers have more or less had the luxury of neglecting maintainability; in the future this will no longer be an option.

Why the need for remote handling, and to what extent can and should it supplant contact operations? Present answers to the why of remote handling are basically three:

1. Module sizes and weights are very large, up to tens of meters and thousands of tons.
2. Well-designed machines can obtain access to areas where humans cannot. They can even in some cases be permanently stationed in situ, obviating some of the need for dismantling or retracting modules.
3. The reactor presents several hostile environments, including high and low temperatures, high vacuum and radiation. Of the three, radiation is the most difficult to shield man against.

In the future, it may be possible to adduce a fourth reason:

4. Remote handling is faster and more efficient than contact.

The last reason stated above for the desirability of remote handling must await considerable advancement in the state of the art. Most studies on maintainability emphasize the preferability of contact operations, and in general, they are preferable. A task undertaken with remote equipment directly controlled by a human operator takes 30 to 100 times as long as if it had been done by contact. For example, performing even very simple tasks with an old-fashioned master-slave manipulator, in which the grasping end mimics the motions of the operator's hand, is akin to trying to knit while wearing boxing gloves. Even with force feedback, human operated remote manipulators take from three to ten times longer than contact operations.

An important feature of remote equipment in the future will be programability, that is, "smart" machines that will be able to be taught to do several tasks without, or partly without, human intervention, and some progress has been made. It is plausible to envision a robot capable of a wide range of motions, and thus able to be taught an almost unlimited variety of tasks. It is also reasonable to suppose that a machine programmed to do a well-defined

job could do so far faster than a human being, and since machines do not get tired or bored, they may be able to do so more reliably. Furthermore, absolutely exact positioning of the tool or part will not be necessary. A human operator using a viewing system may be needed to position the machine roughly, but computer controlled robots can be made somewhat fault-tolerant of small positioning errors through force- and moment-feedback mechanisms and "compliant", or nonrigid robot grips. Thus, a small misalignment between, say, a bolt and bolt hole can be accommodated, and the machine can "wiggle" the part into place. This kind of correction, so simple as to be done almost unconsciously by a man, requires a considerable degree of sophistication in a robot, and is not easy to do. J.L. Nevins and D.E. Whitney, of Charles Stark Draper Laboratory (CSDL), have examined in detail some of the difficulties involved in such compliant machines:

> Care must be taken in designing the strategy so that the right amount of motion is called for in response to the felt force. Too much motion will cause the arm to react as a person does when he touches a hot surface; too little motion will let large contact forces build up to a damaging level. The less stiff (more compliant) the parts and the grippers are and the lighter the arm's moving components are, the easier it is to obtain rapid, stable and effective responses with low contact force. When low stiffness and rapid response motion cannot be built into the apparatus (because for example, it is too heavy or the workpieces it is holding are), the only remedy for avoiding large contact forces is to make all closed-loop motions slowly. This alterntive is an unattractive one from an economic point of view.[42]

Their conclusions, which were reached for assembly machines, but can be extended to maintenance and repair equipment, can be summarized as follows:

1. Particular attention must be paid to the forces and moments at the tip of the object being handled, if it is to be handled properly.

2. Fine and gross motions may have to be done by separate machines or subassemblies. For example, the tasks of positioning a part would be done by a fine motion machine, and the task of positioning the fine motion machine would be done by a gross motion machine.

3. Excess friction can mask contact forces, leading to parts jamming rather than sliding together.

5.2 Design and Economic Considerations

As mentioned before, a CTR must be designed from the ground up with remote handling in mind, or rather, both the reactor and the remote equipment system must be designed with each other in mind. Two examples will serve to illustrate this requirement.

1. When designing, say, those coolant pipes for the reactor which will have to be disconnected remotely, it would be well to consider how to make the job of disassembly as simple as possible with a view of saving time and machine programming costs. Jobs which require a minimum number of

direction changes aid in this goal, so the pipe may be made with a connecting piece that can be simply pulled out (Fig. 20).

2. Other reactor features will not be so amenable to accommodating the remote equipment, and, therefore, the latter must be designed around the reactor. Reactor modules will be so large that even small stresses will lead to large strains. Thus, repeatability will be a problem. Just because two modules fit together at the time of disassembly, one cannot assume that they will automatically fit together when they are to be reassembled. Remote equipment must be of high enough load capacity to correct these strains, and fine enough to do it precisely, and this probably means that humans will not be able to be left out of the process altogether.

Remote operations, while not yet adequate for full-size CTR's, are by no means completely novel. Industrial robots, in such manufacturing procedures as automobile assembly are well-known. So is automatic welding, and Mitsui Engineering & Shipbuilding Co., Ltd. of Japan, has developed a computer-controlled, fully automatic arc-welding robot for use in shipbuilding. CSDL has built a programmable robot which has been taught how to assemble a 17-part automobile alternator from parts brought to it by several conveyers. The robot is adaptable, to allow for standard

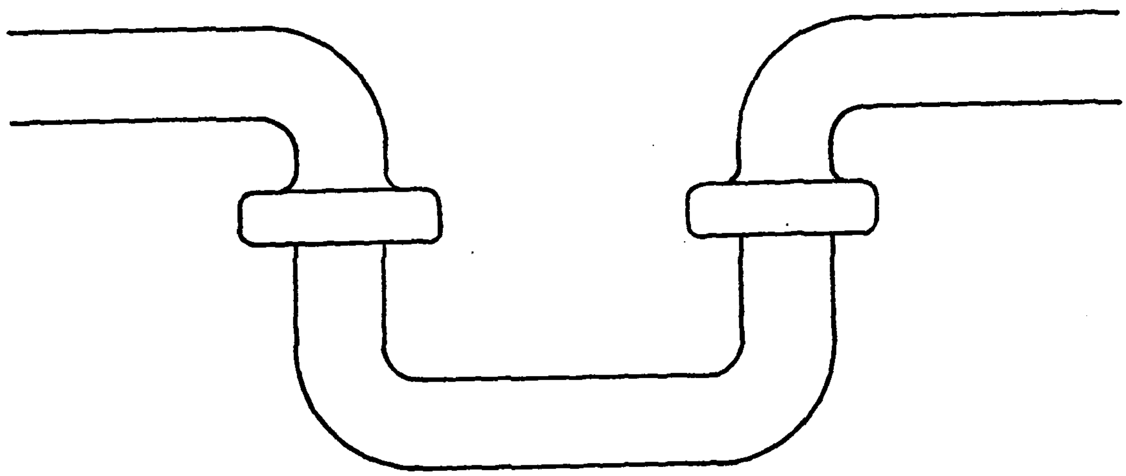


Figure 20. Pipe Fitting Designed for
Ease of Remote Maintenance.

industrial tolerances in the parts, and performs its tasks without human intervention.

Remote operations and maintainability are now being taken into account by fusion system designers as well. In fact, part of the maintenance of TFTR, which produces an internal radioactive environment, is already being done remotely. The primary mission of TFTR is as a physics experiment, and, therefore, some of the remote procedures used on it will be inappropriate for a commerical CTR. Nonetheless, a large portion of the knowledge, techniques and procedures will be applicable. Young, et al[52] describe the major remote equipment, including:

1. The Test Cell/Hot Cell Manipulator, an electromechanical manipulator system mounted on a 110 foot bridge and having a load capacity of 400 pounds and extention capacity of 10 feet. It serves both the main test cell and the neutro beam test cell.

2. In vessel Manipulator System, comprising an arm assembly with two dextrous arms with a load capacity of 20 pounds apiece; an electromachanical 400 pound capacity unit for cutting, conveying, etc.; and associated interface and control equipment.

3. Low Obround Flange Removal Fixture, developed on a TFTR mockup specifically to handle the 400 pound obround flanges located on the bottom of the vacuum vessel between TF coils and obstructed by PF coils.

4. Horizontal Positioner Unit, a high weight capacity unit, also developed at TFTR, able to reach horizontally into obstructed areas and remove components in a horizontal motion.

5. Three electrical connectors, two of which have been especially designed for use with remote equipment.

Studies of remote handling equipment and procedures which are still in the conceptual stage have been performed by McDonnell Douglas and the Fusion Engineering Device (FED) Remote Maintenance Equipment Workshop. The McDonnell Douglas study is of interest because it presents an attempt to design remote handling equipment for four existing designs. The resulting remote maintenance machine design is pictured in Figs. 21 and 22. The study also examined the economic impact of remote handling. Table 7 summarizes the comparison of contact versus remote maintenance for the four designs. It should be remarked here that remote equipment carries a heavy price tag. Present estimates range from $50,000,000 to $150,000,000 per plant, and this is only for the hardware. Development costs could push the price up to 25% of the cost of the plant.

The FED workshop emphasized methods and procedures rather than design, and broke up the remote handling needs into 14 areas:

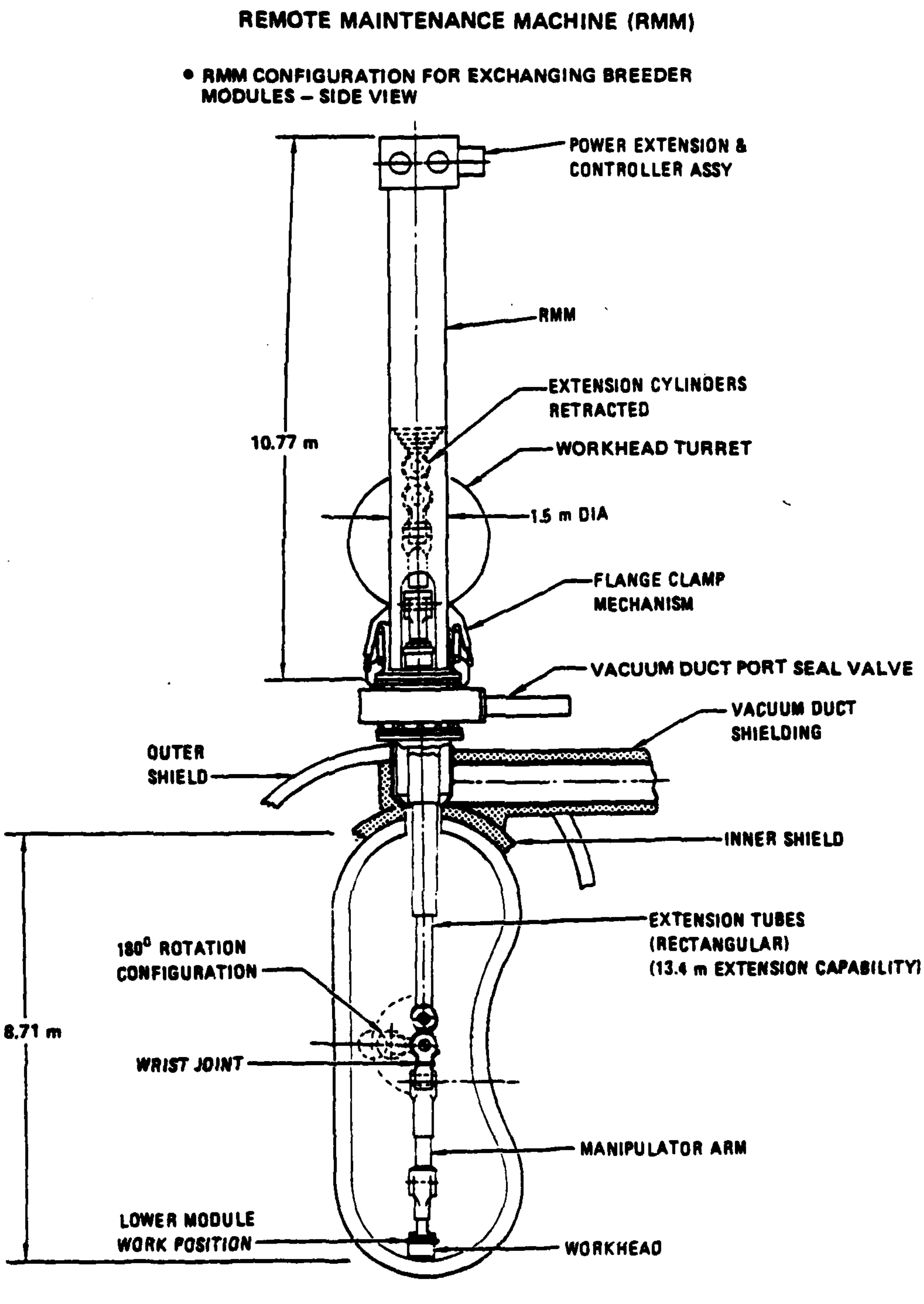


Figure 21. Remote Maintenance Machine (side view).[53]

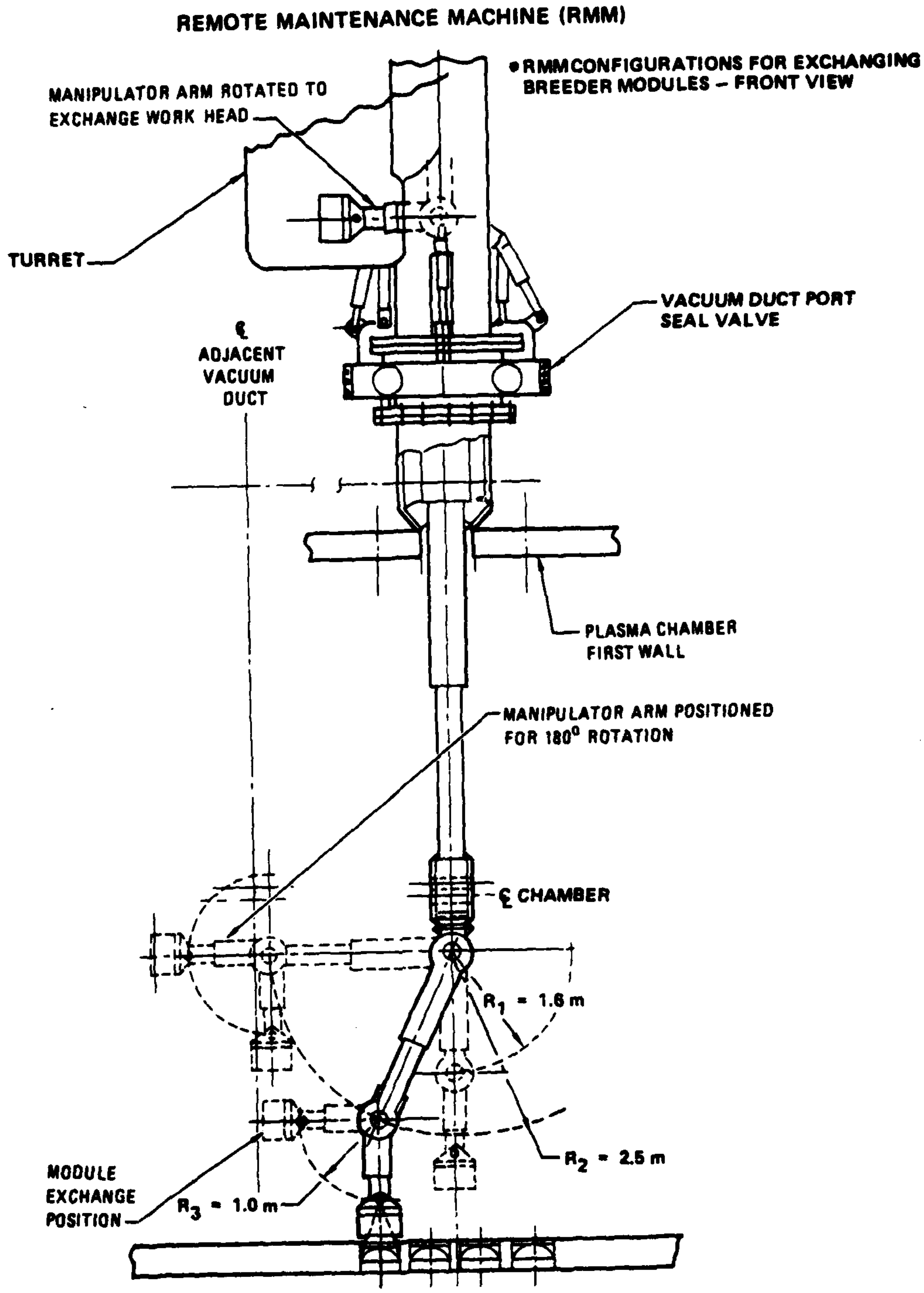


Figure 22. Remote Maintenace Machine (front view).[54]

TABLE 7[5]

SUMMARY OF PARTIAL CONTACT MAINTENANCE DOWNTIME IMPACTS

	UWMAK-III	GA-DOUBLET	CULHAM	ORNL CASSETTE
Total Downtime (Hrs.)[(1)]				
Partial contact maintenance	1023.4	781.3	546.4	988.6
Fully remote maintenance	1408.7	810.8	679.4	1154.0
Percent Reduction with contact	27.4	3.6	19.5	14.3
Downtime for Functions Capable of Using Contact Maintenance[(2)]				
Downtime if using remote maintenance, hrs.	756.8	110.3[(3)]	301.8	418.3
Percent of total	72.0	100	61.2	42.0
Downtime if using contact maintenance, hrs.	385.5	110.3[(3)]	172.3	234.3
Percent of total	56.7	100	47.4	28.9
Total cost of electricity, Mills/kWh[(1)]				
Partial contact maintenance	51.37	53.25[(4)]	50.28	51.01
Fully remote maintenance	53.10	50.93	50.94	51.94
Percent savings with contact	+ 3.2	- 4.3	+ 1.3	+ 1.7

Notes: (1) Data from optimum scheduled first wall/blanket maintenance plans.
(2) Data for single sector first wall/blanket replacement only.
(3) Data for 8 modules only.
(4) Cost increase because of additional shielding cost.

1. Rail-mounted remote maintenance vehicle,
2. Floor mobile manipulators,
3. Powered manipulators,
4. Manipulator transporter and plant configuration,
5. Remote bridge crane,
6. Stereo television viewing system,
7. Manual/remote decontamination system,
8. FED frame seal welder and cutter,
9. Torus sector module handling,
10. Torus sector handling,
11. Leak detection for FED magnets and first wall/shield,
12. Neutral beam injector handling system,
13. Shielding replacement,
14. Remote maintenance needs for FED magnet systems.

Table 8 gives a list of the remote maintenance equipment needed for FED.

So some progress has been made into the ninth circle of the fusion "hell". Maintenance tasks have been identified and analyzed, methods for dealing with them have been proposed and preliminary equipment requirements and designs have been put forward. Most of what is needed in this area could in theory be supplied from existing technology, and the future is likely to see impressive and encouraging developments in making remote handling a reality.

TABLE 8[56]

FED REMOTE MAINTENANCE EQUIPMENT LIST

Item	Remarks
General Purpose	
Manipulators	
Bridge mounted (2)	Interchangeable power manipulator and man-equivalent servomanipulator. Power manipulator with force reflection. Unmanned. Independent arm-mounted stereo TV and lighting. Recovery capability or remotely maintainable.
Floor mobile (2)	(As above, except recovery capability only). Free-rmoving umbilical control with multiple receptacle stations. Anchor stations at operating locations.
Pedestal mounted (4)	(Same as bridge mounted, except recovery capability only). Ten pedestals located co-planar with TF ciols.
Other	
Bridge crane	Five-hundred-ton capacity/25-ton auxiliary capacity. Recovery capability or remotely maintainable.
Modular maintenance vehicle	For handling limiter fuel injectors, test modules, rf launcher, shield plugs, component shield units, diagnostics.
Clamp installation devices	For large coolant lines, diagnostics, and smaller components.
Service connection devices	Adaptable to all service quick disconnects. Installed on manipulator.
Cutters	For Dewars, manifolds, and service lines.
Welders	For Dewars, manifolds, and service lines.
Area lighting and TV viewing	Provide adequate viewing capabilities, independent of building lighting.

(cont'd)

Table 8 (cont'd)

Item	Remarks
Decontamination equipment	Manually and remotely controllable, high pressure, minimal fluid.
Special Purpose	
Electrical	
NBI transporter	Traction drive or cable drive. Track guided. Hydraulic ram or screw jack for breakaway and final positioning.
NBI special tools	For accelerator stack, source, cryopanels, direct recovery assembly, and gas cell.
ICRH handling fixture	
Optical diagnostics special tools	For removal of inside mirrors, vertical mirror assembly, horizontal mirror assembly of optical diagnostics such as the FIR interferometer.
Neutron detector handling tool	
Inspection tools	For various diagnostics.
Magnetic	
Coil handling tools	Slings/fixtures for TF and PF coils.
Coil positioning tools	
Dewar leak detection system	
Leak repair welder	To traverse through 5-cm annular clearance.
Nuclear	
Plasma chamber inspection-maintenance machine	Fiber optics. Rapid changeout TV. Decon capability.

(cont'd)

Table 8 (cont'd)

Item	Remarks
Shield sector transporter	
Sector frame seal transporter	
Sector frame seal handling fixture	
Sector frame seal welder	Self-driven. Installed remotely and manually.
Sector frame seal cutter	Self-driven. Installed remotely and manually.
Limter handling fixture	
Vacuum duct handling fixture	
Test module handling fixture	
Handling casks	For vacuum pumps, diagnostics, fuel injectors, limiters, rf launchers.
Shield plugs	For shield sector, NBI, fuel injector, C&I, and other plasma chamber penetrations.
Shield plug handling fixtures	
Plasma chamber leak detection system	Mass spectrometer.

APPENDIX A[57]

APPENDIX A[57]

HFITR TF MAGNET REPLACEMENT PROCEDURE

Maintenance Action:

Remove lower inboard leg of a defective TF coil.

Assume:

Failure caused inner joint to be welded to the inner vertical leg.

Procedure is as follows:

1. Insert jacks under pads along lower outboard and inboard torque shell between all TF coil bottom sections; raise structure to clear bottom leg.
2. Remove outboard structure assembly at failed magnet location (assume no subsystem ohstructions).
3. Remove TF coil intercostal supports around both sides of defective coil.
4. Support lower outboard leg with cradle or dolly.
5. Disconnect dewar and lower outboard leg joints.
6. Disconnect services to lower outboard and inboard legs.
7. Remove outboard leg of TF coil.
8. Support lower inboard leg with retraction mechanism or dolly.
9. Disconnect dewar and lower inboard leg joint.
10. Attempt to retract lower inboard leg to TF coil.
11. Cut through inboard joint of lower inboard leg of TF coil.
12. Remove lower inboard leg of TF coil.
13. Take up weight of all good coils, structure, shield, and plasma chamber on retractable structure wheels.
14. Disconnect 15 joints between upper collar and outer structural supports.

Appendix A(cont'd)

15. Remove upper retaining ring.

16. Remove upper collar assembly.

17. Remove upper torque plate.

18. Disconnect services to upper inboard leg of TF coil.

19. Disconnect dewar and joints of upper inboard leg of TF coil.

20. Remove upper inboard leg of TF coil.

21. Disconnect services to inboard vertical leg of TF coil.

22. Remove vertical inboard leg of TF coil from reactor.

23. Install replacement vertical inboard leg in reactor.

24. Connect services to vertical inboard leg of TF coil.

25. Install replacement lower inboard leg.

26. Attach inboard joint of lower inboard leg of TF coil. (Retain support in place until outboard leg attachment is completed).

27. Install upper inboard leg of TF coil.

28. Connect joints for upper inboard leg of TF coil.

29. Connect services to upper inboard leg of TF coil.

30. Install upper collar assembly.

31. Install upper retaining ring.

32. Connect 15 joints between upper collar and outer structural supports. (Steps 13 through 20 of maintenance action #1 conducted in parallel with steps 19 through 24 above as follows: Steps 13 through 16 of maintenance action #1 in parallel with steps 19 through 21 above. Steps 17 through 20 of maintenance action #1 in parallel with steps 22 through 24 above).

Appendix A(cont'd)

33. Complete installation of lower outboard leg of TF coil.

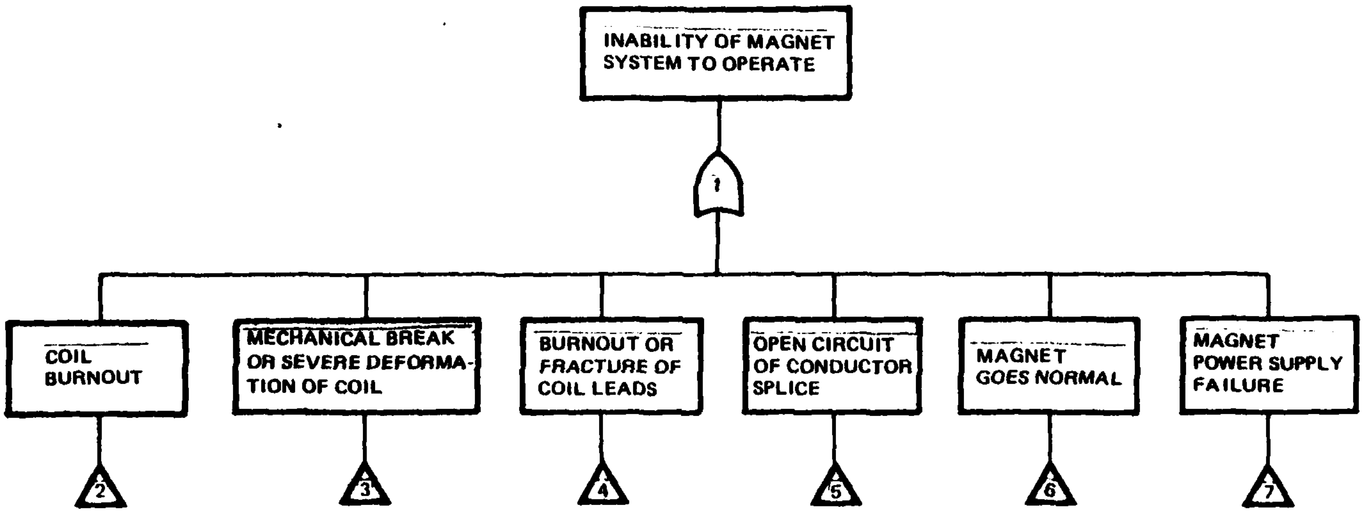
34. Preload all structural support joints in tension.

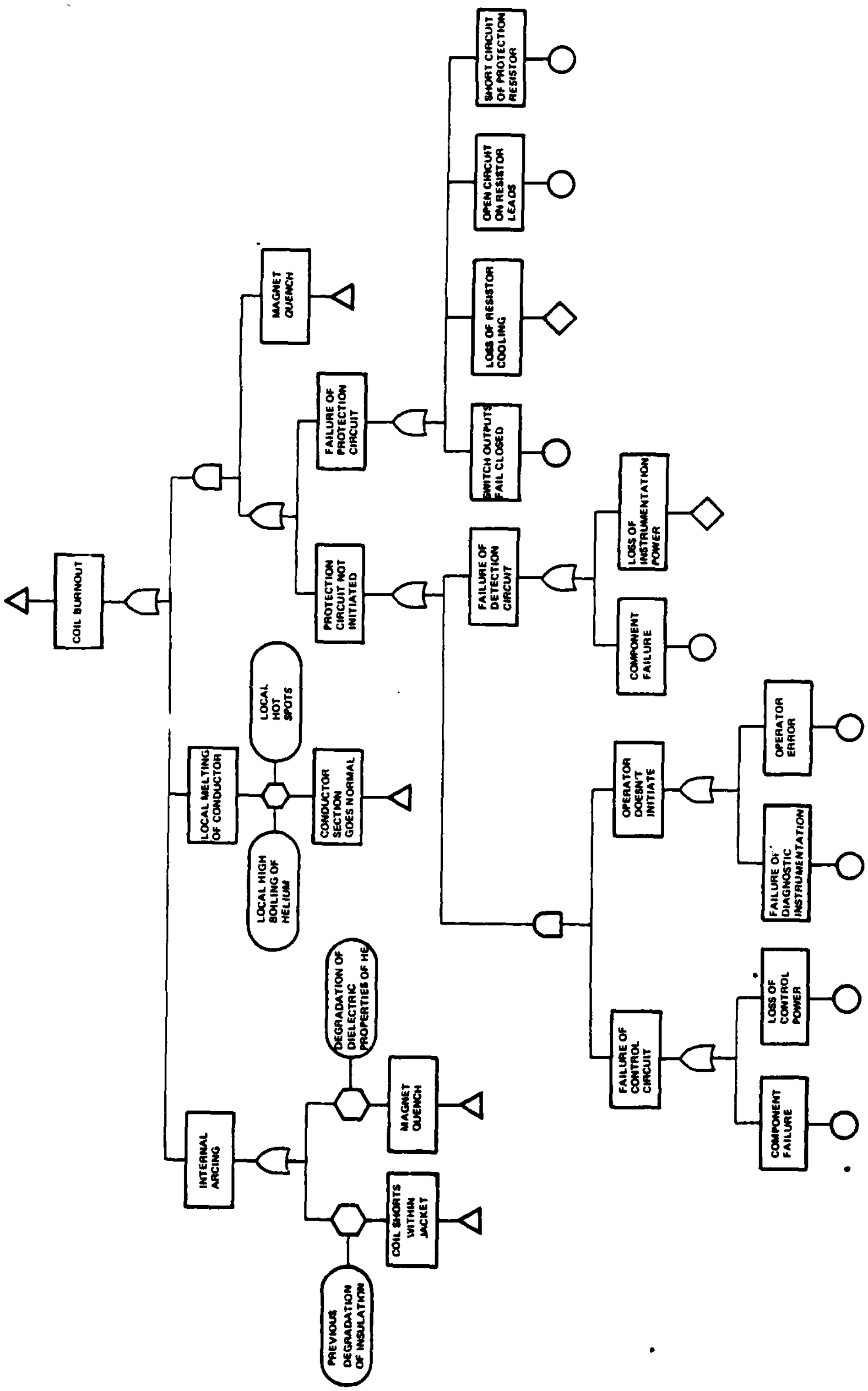
35. Retract wheels to transfer loads to outer structural supports.

36. Chill down and electrically test repaired coil.

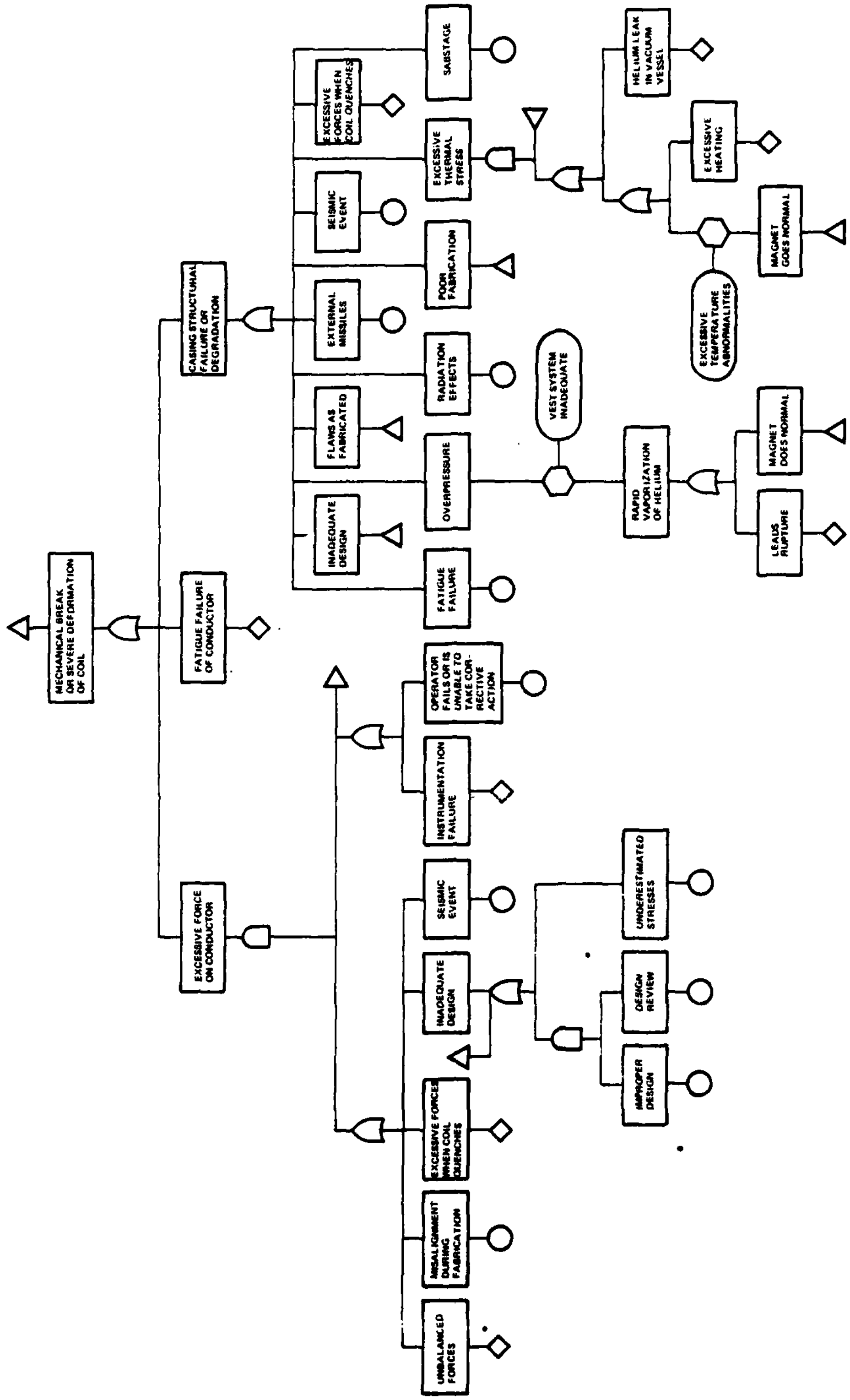
APPENDIX B[58]

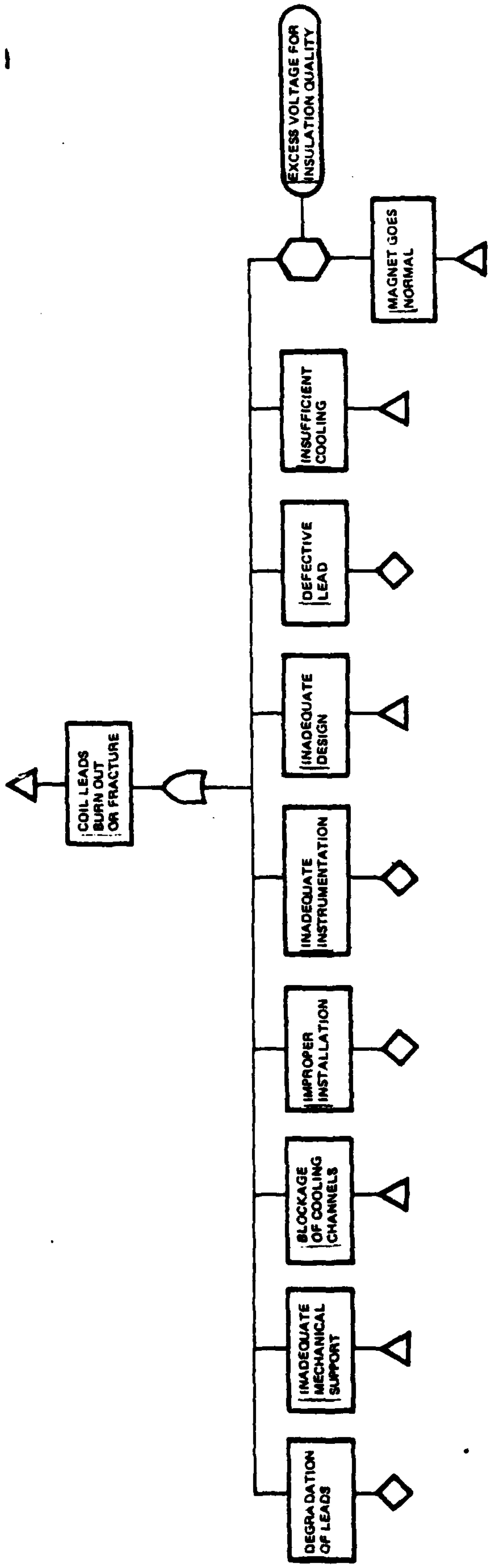
MFTF Magnet System Fault Tree

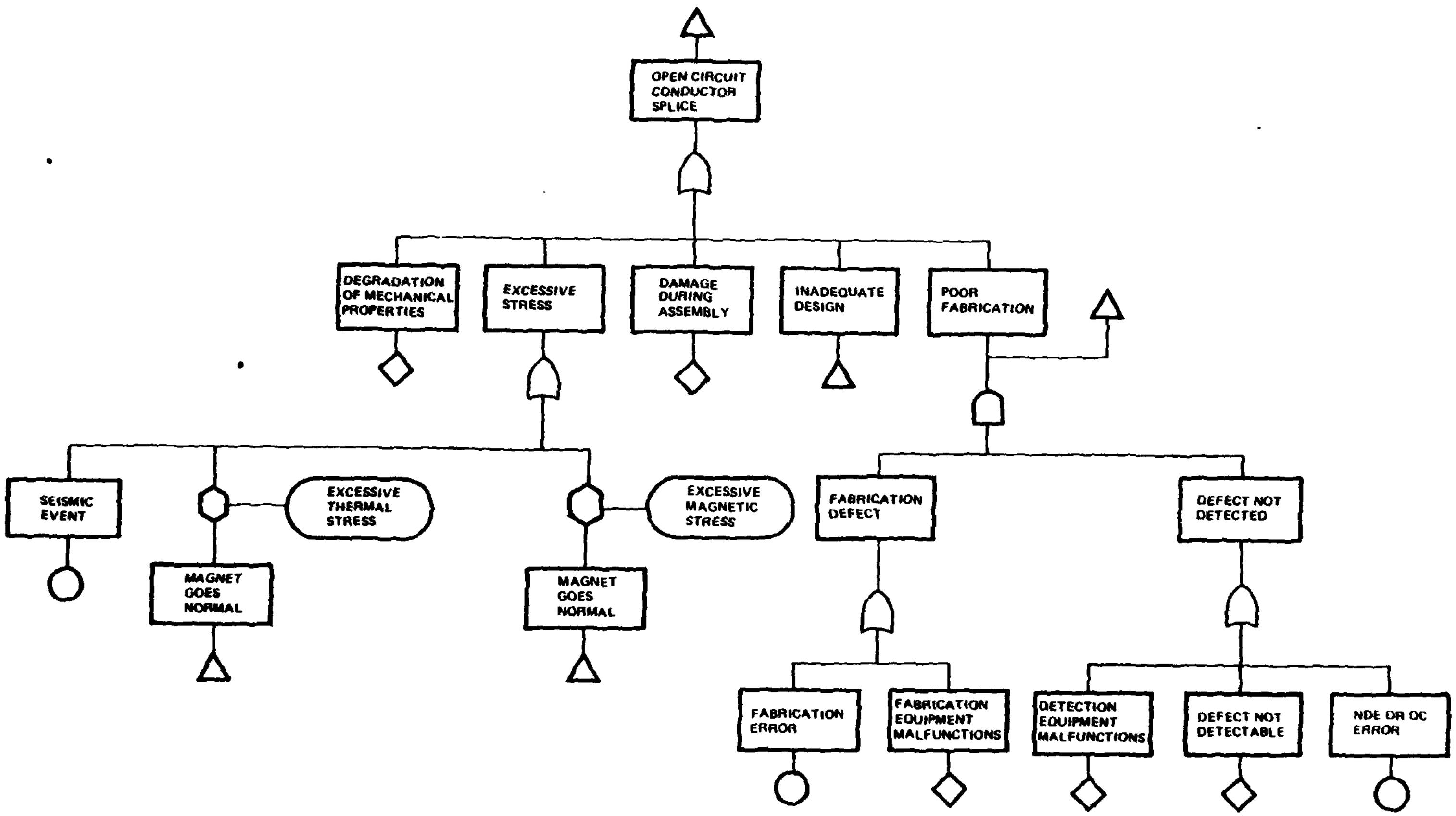

INABILITY OF MAGNET SYSTEM TO OPERATE
1
COIL BURNOUT
MECHANICAL BREAK OR SEVERE DEFORMATION OF COIL
BURNOUT OR FRACTURE OF COIL LEADS
OPEN CIRCUIT OF CONDUCTOR SPLICE
MAGNET GOES NORMAL
MAGNET POWER SUPPLY FAILURE
2
3
4
5
6
7

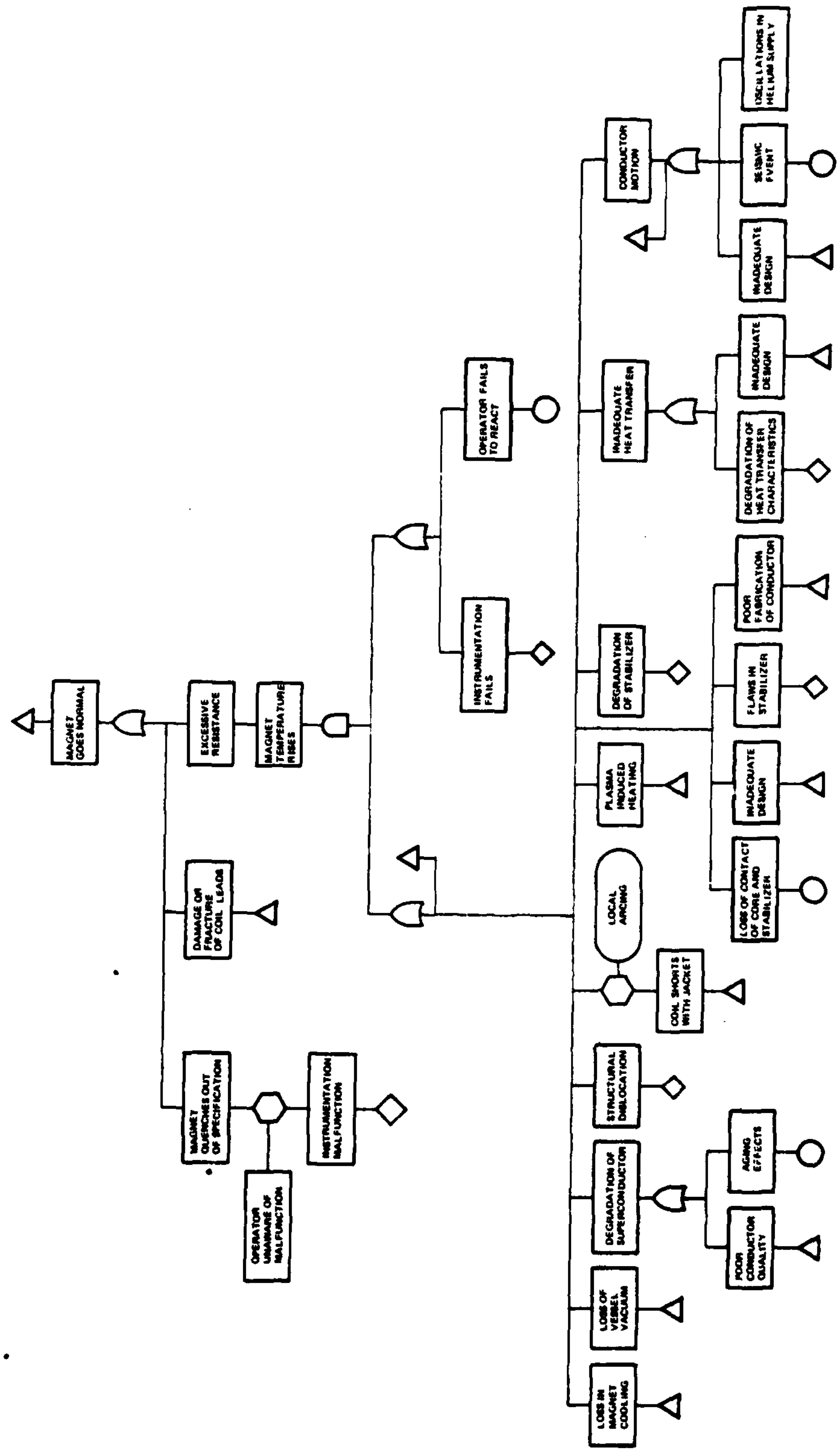


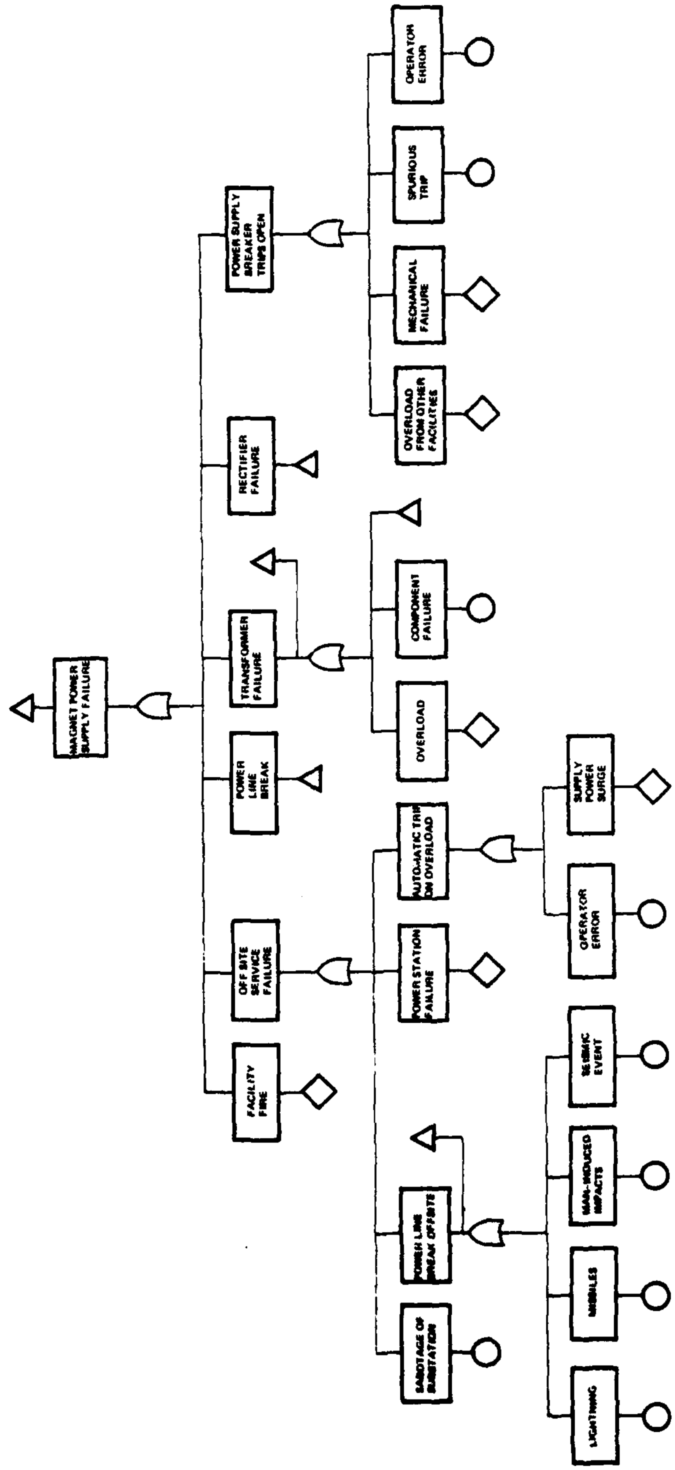
COIL BURNOUT
LOCAL MELTING OF CONDUCTOR
INTERNAL ARCING
MAGNET QUENCH
FAILURE OF PROTECTION CIRCUIT
PROTECTION CIRCUIT NOT INITIATED
SHORT CIRCUIT OF PROTECTION RESISTOR
OPEN CIRCUIT ON RESISTOR LEADS
LOSS OF RESISTOR COOLING
SWITCH OUTPUTS FAIL CLOSED
FAILURE OF DETECTION CIRCUIT
LOSS OF INSTRUMENTATION POWER
COMPONENT FAILURE
LOCAL HOT SPOTS
LOCAL HIGH BOILING OF HELIUM
CONDUCTOR SECTION GOES NORMAL
OPERATOR DOESN'T INITIATE
OPERATOR ERROR
FAILURE OF DIAGNOSTIC INSTRUMENTATION
LOSS OF CONTROL POWER
FAILURE OF CONTROL CIRCUIT
COMPONENT FAILURE
DEGRADATION OF DIELECTRIC PROPERTIES OF HE
MAGNET QUENCH
COIL SHORTS WITHIN JACKET
PREVIOUS DEGRADATION OF INSULATION

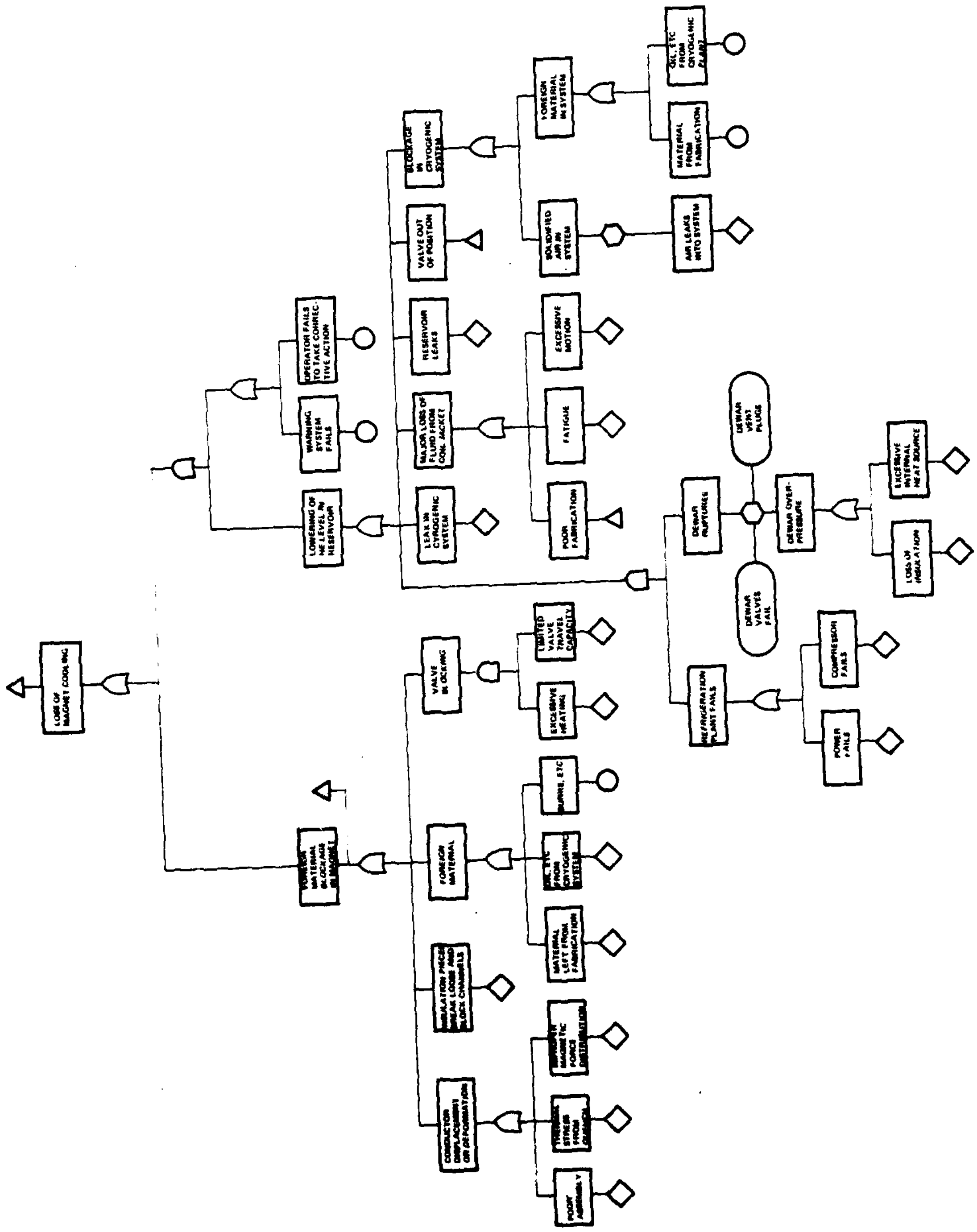

MECHANICAL BREAK OR SEVERE DEFORMATION OF COIL
FATIGUE FAILURE OF CONDUCTOR
CASING STRUCTURAL FAILURE OR DEGRADATION
EXCESSIVE FORCE ON CONDUCTOR
INADEQUATE DESIGN
FLAWS AS FABRICATED
EXTERNAL MISSILES
SEISMIC EVENT
EXCESSIVE FORCES WHEN COIL QUENCHES
SABSTAGE
FATIGUE FAILURE
OVERPRESSURE
RADIATION EFFECTS
POOR FABRICATION
EXCESSIVE THERMAL STRESS
VEST SYSTEM INADEQUATE
RAPID VAPORIZATION OF HELIUM
MAGNET DOES NORMAL
LEADS RUPTURE
EXCESSIVE TEMPERATURE ABNORMALITIES
MAGNET GOES NORMAL
EXCESSIVE HEATING
HELIUM LEAK IN VACUUM VESSEL
OPERATOR FAILS OR IS UNABLE TO TAKE COR-RECTIVE ACTION
INSTRUMENTATION FAILURE
SEISMIC EVENT
INADEQUATE DESIGN
UNDERESTIMATED STRESSES
DESIGN REVIEW
IMPROPER DESIGN
EXCESSIVE FORCES WHEN COIL QUENCHES
MISALIGNMENT DURING FABRICATION
UNBALANCED FORCES

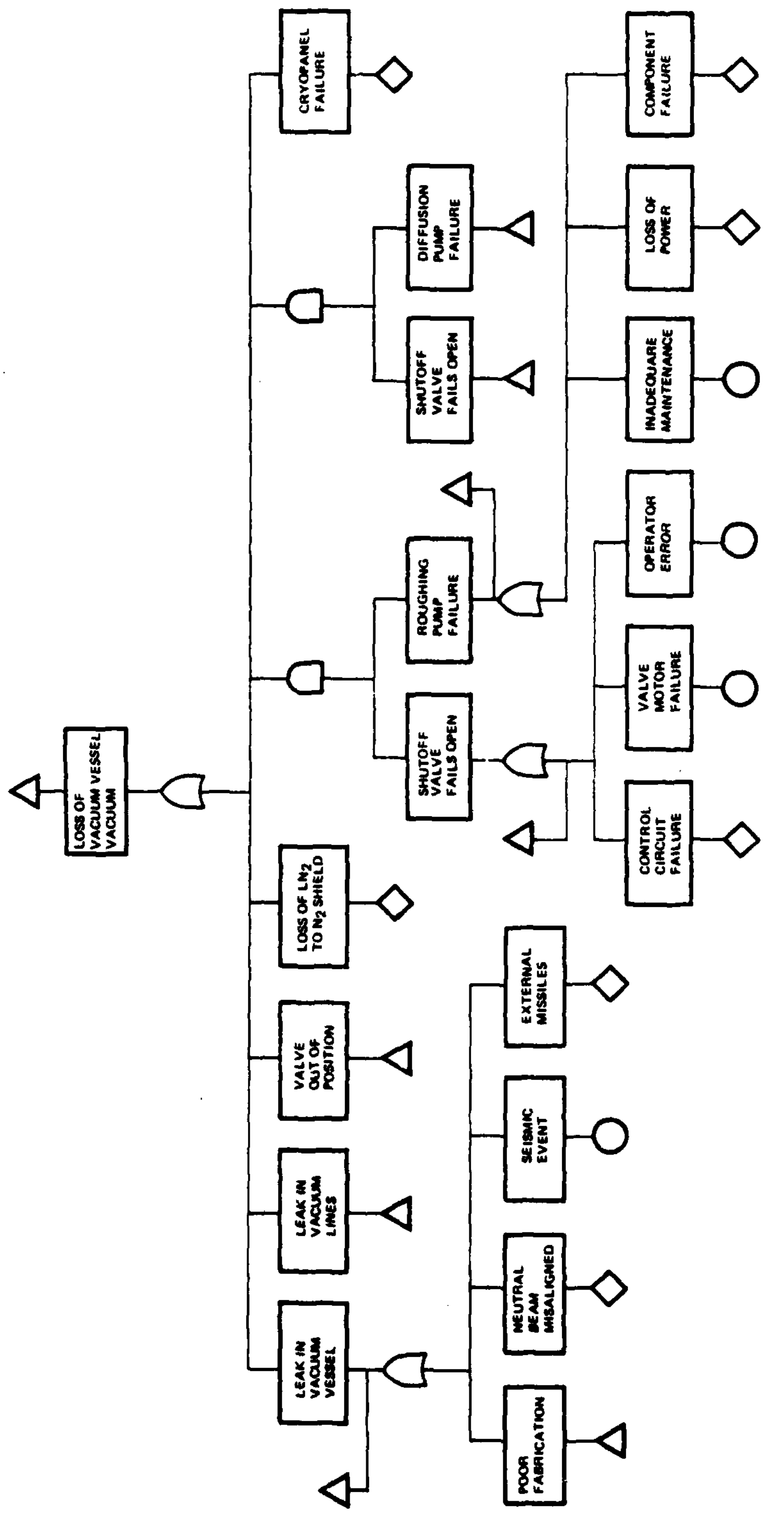

COIL LEADS BURN OUT OR FRACTURE
DEGRADATION OF LEADS
INADEQUATE MECHANICAL SUPPORT
BLOCKAGE OF COOLING CHANNELS
IMPROPER INSTALLATION
INADEQUATE INSTRUMENTATION
INADEQUATE DESIGN
DEFECTIVE LEAD
INSUFFICIENT COOLING
MAGNET GOES NORMAL
EXCESS VOLTAGE FOR INSULATION QUALITY

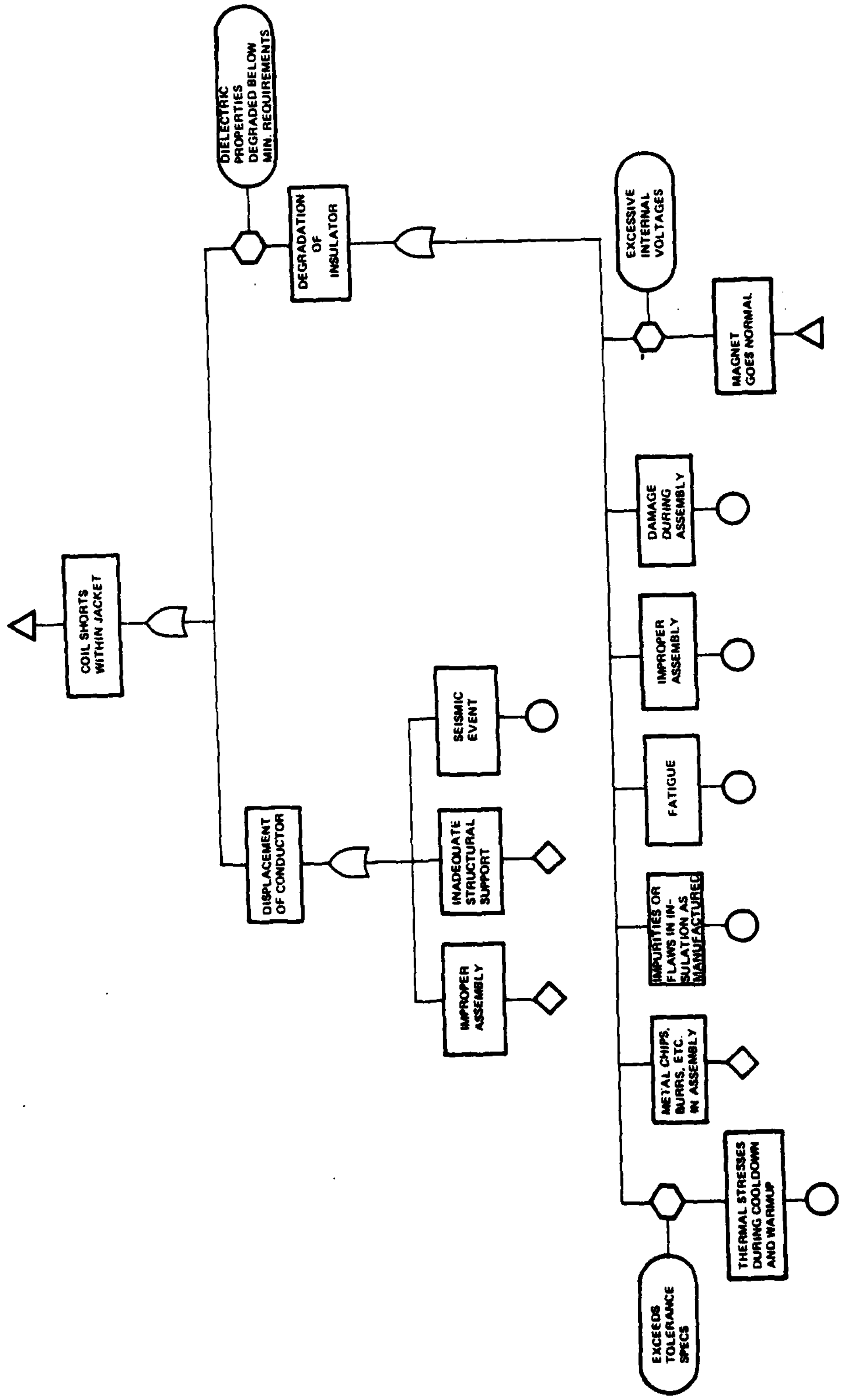

OPEN CIRCUIT CONDUCTOR SPLICE
DEGRADATION OF MECHANICAL PROPERTIES
EXCESSIVE STRESS
DAMAGE DURING ASSEMBLY
INADEQUATE DESIGN
POOR FABRICATION
SEISMIC EVENT
EXCESSIVE THERMAL STRESS
MAGNET GOES NORMAL
EXCESSIVE MAGNETIC STRESS
MAGNET GOES NORMAL
FABRICATION DEFECT
DEFECT NOT DETECTED
FABRICATION ERROR
FABRICATION EQUIPMENT MALFUNCTIONS
DETECTION EQUIPMENT MALFUNCTIONS
DEFECT NOT DETECTABLE
NDE OR QC ERROR


MAGNET GOES NORMAL
EXCESSIVE RESISTANCE
MAGNET TEMPERATURE RISES
DAMAGE OR FRACTURE OF COIL LEADS
MAGNET QUENCHES OUT OF SPECIFICATION
OPERATOR UNAWARE OF MALFUNCTION
INSTRUMENTATION MALFUNCTION
OPERATOR FAILS TO REACT
INSTRUMENTATION FAILS
LOSS IN MAGNET COOLING
LOSS OF VESSEL VACUUM
DEGRADATION OF SUPERCONDUCTOR
STRUCTURAL DISLOCATION
COIL SHORTS WITH JACKET
LOCAL ARCING
PLASMA INDUCED HEATING
DEGRADATION OF STABILIZER
INADEQUATE HEAT TRANSFER
CONDUCTOR MOTION
POOR CONDUCTOR QUALITY
AGING EFFECTS
LOSS OF CONTACT OF CORE AND STABILIZER
INADEQUATE DESIGN
FLAWS IN STABILIZER
POOR FABRICATION OF CONDUCTOR
DEGRADATION OF HEAT TRANSFER CHARACTERISTICS
INADEQUATE DESIGN
INADEQUATE DESIGN
SEISMIC EVENT
OSCILLATIONS IN HELIUM SUPPLY


MAGNET POWER SUPPLY FAILURE
FACILITY FIRE
OFF SITE SERVICE FAILURE
POWER LINE BREAK
TRANSFORMER FAILURE
RECTIFIER FAILURE
POWER SUPPLY BREAKER TRIPS OPEN
SABOTAGE OF SUBSTATION
POWER LINE BREAK OFFSITE
POWER STATION FAILURE
AUTOMATIC TRIP ON OVERLOAD
OVERLOAD
COMPONENT FAILURE
OVERLOAD FROM OTHER FACILITIES
MECHANICAL FAILURE
SPURIOUS TRIP
OPERATOR ERROR
LIGHTNING
MISSILES
MAN-INDUCED IMPACTS
SEISMIC EVENT
OPERATOR ERROR
SUPPLY POWER SURGE


LOSS OF MAGNET COOLING
LOWERING OF HE LEVEL IN RESERVOIR
WARNING SYSTEM FAILS
OPERATOR FAILS TO TAKE CORREC-TIVE ACTION
LEAK IN CRYOGENIC SYSTEM
MAJOR LOSS OF FLUID FROM CON. JACKET
RESERVOIR LEAKS
VALVE OUT OF POSITION
BLOCKAGE IN CRYOGENIC SYSTEM
POOR FABRICATION
FATIGUE
EXCESSIVE MOTION
SOLIDIFIED AIR IN SYSTEM
FOREIGN MATERIAL IN SYSTEM
AIR LEAKS INTO SYSTEM
MATERIAL FROM FABRICATION
OIL, ETC FROM CRYOGENIC PLANT
DEWAR RUPTURES
DEWAR VENT PLUGS
DEWAR VALVES FAIL
DEWAR OVER-PRESSURE
EXCESSIVE INTERNAL HEAT SOURCE
LOSS OF INSULATION
REFRIGERATION PLANT FAILS
COMPRESSOR FAILS
POWER FAILS
VALVE BLOCKING
LIMITED VALVE TRAVEL CAPACITY
EXCESSIVE HEATING
FOREIGN MATERIAL BLOCKAGE IN MAGNET
FOREIGN MATERIAL
BURRS, ETC
OIL, ETC FROM CRYOGENIC SYSTEM
MATERIAL LEFT FROM FABRICATION
INSULATION PIECES BREAK LOOSE AND BLOCK CHANNELS
CONDUCTOR DISPLACEMENT OR DEFORMATION
MAGNETIC FORCE DISTRIBUTION
POOR ASSEMBLY


LOSS OF VACUUM VESSEL VACUUM
CRYOPANEL FAILURE
SHUTOFF VALVE FAILS OPEN
DIFFUSION PUMP FAILURE
SHUTOFF VALVE FAILS OPEN
ROUGHING PUMP FAILURE
LOSS OF LN_2 TO N_2 SHIELD
VALVE OUT OF POSITION
LEAK IN VACUUM LINES
LEAK IN VACUUM VESSEL
COMPONENT FAILURE
LOSS OF POWER
INADEQUARE MAINTENANCE
OPERATOR ERROR
VALVE MOTOR FAILURE
CONTROL CIRCUIT FAILURE
EXTERNAL MISSILES
SEISMIC EVENT
NEUTRAL BEAM MISALIGNED
POOR FABRICATION


COIL SHORTS WITHIN JACKET
DEGRADATION OF INSULATOR
DIELECTRIC PROPERTIES DEGRADED BELOW MIN. REQUIREMENTS
EXCESSIVE INTERNAL VOLTAGES
MAGNET GOES NORMAL
DAMAGE DURING ASSEMBLY
IMPROPER ASSEMBLY
FATIGUE
IMPURITIES OR FLAWS IN IN-SULATION AS MANUFACTURED
METAL CHIPS, BURRS, ETC. IN ASSEMBLY
THERMAL STRESSES DURING COOLDOWN AND WARMUP
EXCEEDS TOLERANCE SPECS
DISPLACEMENT OF CONDUCTOR
SEISMIC EVENT
INADEQUATE STRUCTURAL SUPPORT
IMPROPER ASSEMBLY

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